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FINAL REPORT

DEVELOPMENT OF OPTIMUM FABRICATION TECHNIQUES FOR BRAZED Ta/TYPE 316 SS TUBULAR TRANSITION JOINTS

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-11846
Phillip Stone, Project Manager
Materials and Structures Division

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ABSTRACT

Optimum techniques were developed for the brazing and ultrasonic inspection of tantalum/Type 316 stainless steel, tongue-in-groove design, tubular transition joints. Experiments were conducted, which established those brazing conditions most conducive toward elimination of braze microshrinkage in the joint areas. Ultrasonic inspection methods were developed for measuring the quality of the brazed joints. Twelve 2-inch-OD joints for subsequent evaluation testing and usage in the SNAP-8 Power Conversion System were brazed and found satisfactory by implementation of the developed ultrasonic method of inspection.

SUMMARY

The primary objectives of this program were to develop optimum techniques for the brazing of tantalum/Type 316 stainless steel, tongue-in-groove design, tubular transition joints and to generate a reliable ultrasonic inspection method for determining the quality of such assemblies. An additional requirement was that twelve 2-inch-OD x 0.120-inch-wall production joints be fabricated and inspected, utilizing those developed methods, for subsequent evaluation testing. To achieve the initial goals, several sheet and tubular sample assemblies were vacuum brazed with a J-8400 brazing alloy, ultrasonically inspected, and destructively evaluated. Specific parameters, used in sample brazing, were varied until optimum (minimum braze microshrinkage) conditions were realized, as determined by ultrasonic and subsequent microstructural examinations. The parameters studied were steady state and transient temperature distribution conditions across the braze area during brazing and subsequent cooling cycles, and the basic cooling rates during solidification of the braze alloy. A wide range in ultrasonic inspection sensitivities was initially employed to permit selection of the most appropriate limits. Detailed comparisons of sample microstructural examination data, with the ultrasonic presentations for a particular joint, established the degree of correlation and identified meaningful ultrasonic sensitivity levels for further inspections.

The experimentation revealed that minimum braze microshrinkage could be achieved by brazing at 2160°F (1182°C)/5 minutes or 2250°F (1232°C)/1 minute and cooling at a rate of 25°F (14°C)/minute during braze solidification. Limited testing also indicated that intentional solidification of the braze, in a specific selected direction within the tongue-and-groove area, would not substantially improve the brazing characteristics. The capability of ultrasonics to accurately depict the brazing characteristics in the bimetallic transition joints was demonstrated by correlation of inspection data with physical microstructures of three actual prototype joints. Twelve 2-inch-OD tubular

production joints were successfully brazed and their quality verified by ultrasonic inspection. These joints were made available to NASA-LRC for subsequent evaluation testing or usage in the SNAP-8 Power Conversion System.

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I. INTRODUCTION

Tubular transition joints between the refractory metals, columbium, tantalum, molybdenum, and their alloys, and the more conventional structural materials, such as stainless steels and the nickel or cobalt-base superalloys, are necessary components of advanced turboelectric space power systems. For the SNAP-8 Power Conversion System,* transitions between unalloyed tantalum and Type 316 stainless steel are required at the inlet and exit of the mercury boiler. Coextrusion and brazing are being considered for fabricating these bimetallic tubular subassemblies. Vacuum brazing with the cobalt-base braze alloy, J-8400,** has been utilized by GE-NSP for the construction of both 0.75-inch-OD and 2.5-inch-OD tantalum-to-Type 316 stainless steel, tongue-in-groove design, tubular test assemblies. Mercury thermal shock testing of several of these brazed joints, under conditions more severe than expected in operation of the SNAP-8 system, indicated the basic reliability of the brazing technique (Reference 1, 2). However, posttest destructive evaluation revealed that alterations in the brazing techniques would be necessary to reduce the formation of microshrinkage voids in the solidified braze alloy, and thereby improve the quality of the assemblies. It was also indicated that the nondestructive inspection method (ultrasonics) needed refinement to adequately identify the braze solidification characteristics in the tongue and groove area.

The equilibrium metallurgical reactions during brazing of refractory/nonrefractory metal joints result in the formation of intermetallic phases having very low ductilities, generally much less than that of the parent metals. The significantly different coefficients of thermal expansion for the bimetallic joint components must also be accommodated during the brazing operation. Both of these factors must be considered during design and fabrication to produce joints which will exhibit satisfactory strength and

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* SNAP-8 Refractory Boiler Development Program, NASA Contract NAS 3-10610.

** J-8400, nominal composition: Co-21Cr-21Ni-8Si-3.5W-0.8B-0.4C.

stability during elevated temperature service. The tongue-in-groove design approach has been successfully utilized to fabricate Cb-1Zr/stainless steel and molybdenum/Haynes' alloy No. 25 brazed tube joints (Reference 3). In the majority of those cases, the joint components were machined such that the tongue members were of nonrefractory metal, while the refractory metal members contained grooves. The previously tested SNAP-8 type bimetallic joints were prepared in that manner with the stainless steel and tantalum being the tongue and groove, respectively. Recent theoretical stress analyses have shown that utilization of the reverse design configuration (i.e., refractory metal tongue and stainless steel groove) would result in assemblies having superior resistance to failure under anticipated SNAP-8 thermal cycling service exposures (Reference 4). Easier machining and prebraze component cleaning, and superior braze alloy capillary flow conditions at the brazing temperature are other practical aspects which make that approach more attractive. For these reasons, the tantalum tongue-stainless steel groove general design configuration was selected for further investigation in this development program.

The overall purpose of this program was to optimize techniques for the fabrication of 2-inch OD by 0.12-inch wall brazed tantalum/Type 316 stainless steel tubular transition joints. The initial program objective was to investigate those variables which influence the braze flow and solidification characteristics and associated metallurgical reactions. Those factors include brazing temperature, time at brazing temperature, cooling rate during braze solidification, and the design of component parts to achieve the desired assembly fit-up characteristics. The data obtained from those investigations were used to establish the best fabrication techniques. A further purpose of this study was to develop a reliable ultrasonic technique for the postbraze nondestructive inspection of the tantalum/stainless steel joints to assure their quality. Subsequent to the investigation and development of the brazing and inspection methods, twelve, 2-inch OD by 0.12-inch wall assemblies were manufactured utilizing the optimized techniques. These joints were prepared for use in the boiler of the SNAP-8 Power Conversion System and for additional evaluation testing which will assist in establishing the acceptance criteria for tantalum/stainless steel brazed transition joints.

II. EXPERIMENTAL PROCEDURES

TECHNICAL APPROACH

The tantalum/Type 316 stainless steel braze optimization study was conducted in three general phases; i.e., Brazing Thermal Parameter Studies, Correlation Studies, and Production Joint Fabrication.

Some of the specific objectives of the brazing thermal parameter studies were to establish (1) the cooling rate during solidification of the J-8400 braze alloy, which minimized microshrinkage void formation; (2) possible effects of microshrinkage voids on representative brazed joints tensile properties; (3) the possibility of directional braze solidification for reducing void formation; and (4) the effects of heat shielding and associated tubular joint temperature distribution on minimizing void formation. The results obtained from these determinations permitted the selection of the best conditions for fabrication of tantalum/Type 316 stainless steel tubular brazed joints. An additional goal of the braze parameter studies was to determine preliminary techniques for ultrasonic inspection of brazed bimetallic joints.

The effects of cooling rate variations on the freezing characteristics of the J-8400 braze alloy were investigated by the vacuum brazing of both simple overlap and tongue-in-groove tantalum/Type 316 stainless steel sheet samples. The overlap specimens were individually brazed, using a fixed heating rate and brazing temperature, and then cooled at several preselected rates to provide a range of solidification conditions. Microstructural examination of the overlap samples was employed to establish the rate which resulted in the least microshrinkage void formation. Several tongue-in-groove sheet specimens were then produced. These specimens were tensile tested at elevated temperatures to determine the effect of different cooling rates on the joint properties. In addition, several tubular assemblies were brazed, using different thermal shielding and a fixed cooling rate, to determine which shielding condition produced the best joint properties, as identified by ultrasonic inspection.

The potential capability of directional braze solidification for reducing the extent of microshrinkage void formation in tubular tongue-in-groove joints was explored by the vacuum brazing of two assemblies under conditions expected to be conducive for producing that effect. The basic technique utilized involved positioning of heat shielding around the tantalum joint components to reduce radiant heat losses from those members during cooling from the brazing temperature. The variables, systematically evaluated before preparation of the indicated joints, included number and position of heat shields, geometry of heat shields, position of the joint in the vacuum furnace, and the overall assembly cooling rate.

The development of a reliable ultrasonic inspection technique for the postbraze nondestructive inspection of the tubular braze joints was implemented by the preparation of suitable inspection standards and the subsequent inspection of representative tubular sample assemblies. These sample assemblies were metallographically examined in detail to provide comparison data of the physical microstructures and the corresponding ultrasonic presentations obtained from a nominally selected area. These data were used to define the nature of the ultrasonic indications and thereby establish meaningful sensitivites for inspection of subsequent brazed joints. Particular emphasis was placed on demonstrating that the ultrasonic method could accurately identify significant structural defects, such as braze porosity, cracks or separations in the assemblies, and areas of complete nonbonding between the braze and parent metals, as well as indicating the exact position and relative size of a given defect. Microhardness traverse testing was performed on all metallographic planes of examination to assist in the identification of braze-base metal metallurgical reactions.

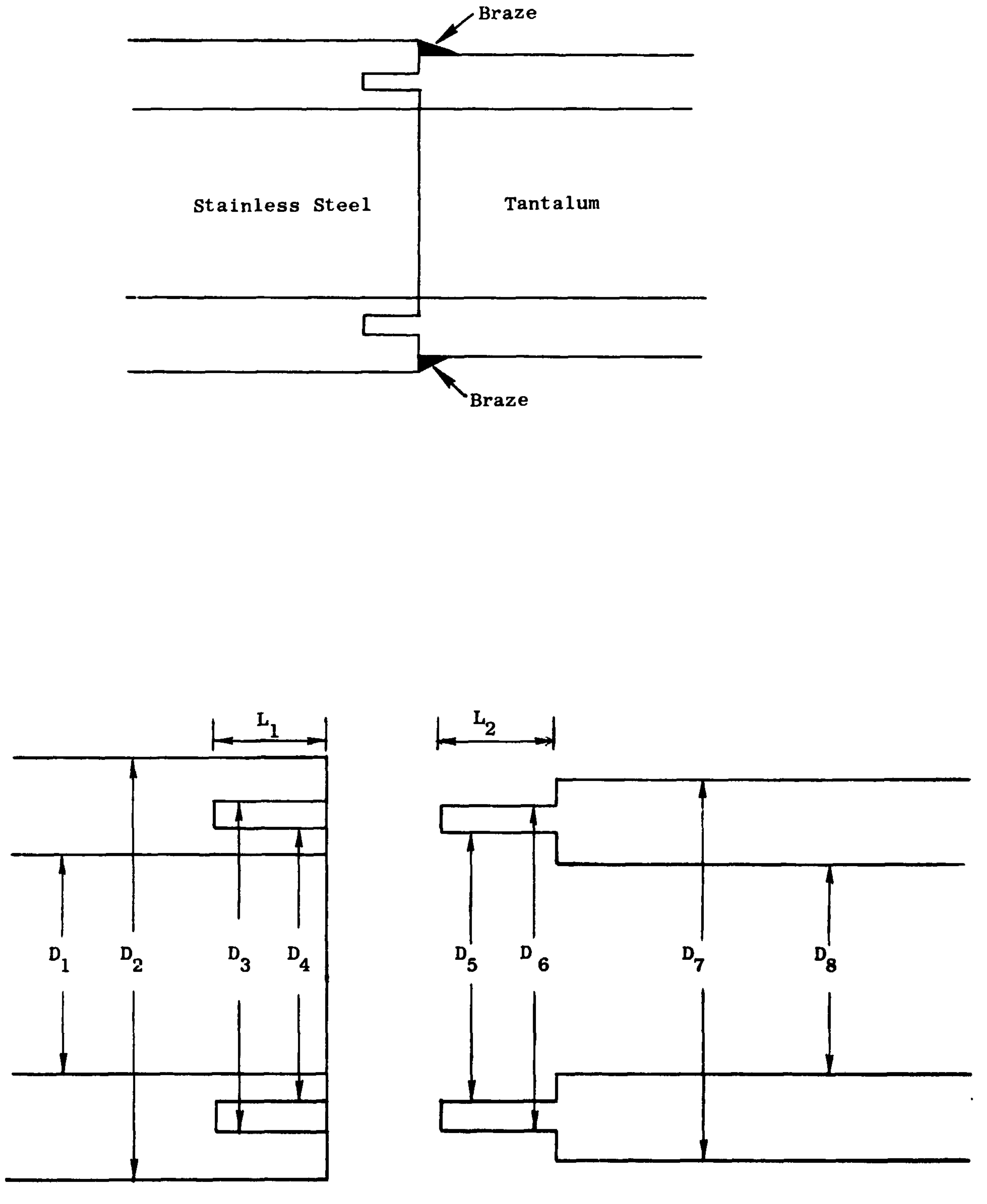
The production joint fabrication phase of the investigation consisted of first selecting the optimum procedures based on the results generated in the previous parameter studies. Twelve tubular joints were fabricated by those procedures and subsequently inspected using the developed ultrasonic technique to assure their internal quality. Other nondestructive inspection tools, such as helium mass spectrometric leak testing and dye penetrant inspection, were also employed to assure the integrity of the assemblies.

A tantalum tongue-stainless steel groove design configuration was utilized for all tubular assemblies construction. Practical design considerations were the thermal expansion mismatch between the parent metals, the length of the tongue and groove to provide desired shear load support areas, and the required overall configuration of the resultant brazed assemblies. The determination of the radial tongue and groove dimensions was based on (1) the difference in expansion of tantalum and Type 316 stainless steel on heating and cooling from an initially selected 2160°F (1182°C) brazing temperature, and (2) a desired capillary flow spacing at the inside of the tongue and groove (radial clearance) at 2160°F (1182°C) of 0.002 inch to 0.003 inch. Reduction of that spacing during later program joint fabrication was realized by increasing the brazing temperature.

DESIGN CONSIDERATIONS

The mean coefficients of thermal expansion for tantalum and Type 316 stainless steel are $\alpha = 3.6 \times 10^{-6}$ in/in/°F (6.5×10^{-6} cm/cm/°C) and 10.5×10^{-6} in/in/°F (2.0×10^{-5} cm/cm/°C), respectively. A primary function of the design of tubular transition joints between those materials is to accommodate that relatively large difference in expansion during heating and/or cooling between ambient and elevated temperatures. One configuration that has been shown to be suitable for the preparation of reliable transition joints is that of the tongue-in-groove (References 1, 2, and 4).

The critical dimensions, pertinent to the tongue-in-groove geometry, are presented in Figure 1. The temperatures, utilized in brazing (nominally 2160°F (1182°C) for J-8400 braze alloy) are necessarily higher than those which might be encountered in service. Thus, the brazing operation actually



Critical Joint Dimensions

Figure 1. Brazed Bimetallic Joint Design

establishes the required interrelated dimensions of the component parts. The majority of previously fabricated, SNAP-8 type, tubular bimetallic brazed assemblies were prepared using a stainless steel tongue-tantalum groove configuration. Recent theoretical stress analyses have indicated that a more favorable state of stress would be associated with the reverse approach for the tantalum/Type 316 stainless steel materials combination; i.e., tantalum tongue, stainless steel groove, and that basic design was, therefore, selected for this optimization study. The following will point out some of the pertinent design considerations regarding tubular tantalum tongue-stainless steel groove assemblies (refer to Figure 1).

The necessary spacings, at the brazing temperature, between the inside and outside of the tongue and groove, are determined from the following differential expansion equation as applied to both joint components:

$$D_f = D_o \ (1 + \alpha \ \Delta T)$$

where:

D_f = tongue or groove diameter at the brazing temperature, inches;

D_o = tongue or groove diameter initially, inches;

α = mean coefficient of thermal expansion for either tantalum or Type 316 stainless steel at the brazing temperature, in/in/°F; and

$\Delta T = T_f - T_o$ = temperature change in brazing, °F.

Referring to the tantalum tongue design, the outside diameters of the tongue and groove (D_3 and D_6) must be machined to the closest possible fitup at room temperature, since the differential expansion on heating to the brazing temperature will produce a relatively large annular spacing in that area, which must be filled by the braze alloy. The difference in the coefficients of thermal expansion for tantalum and Type 316 stainless steel, $\alpha_{ss} - \alpha_{Ta}$, equals approximately 6 x 10^{-6} in/in/°F. Thus, for initially equal diameters, D_3 and D_6, of 2.0 inch, the annular radial clearance at 2160°F (1182°C) would be 0.012 inch.

Complete filling of that zone by the brazing alloy can be more readily achieved in joints of the tantalum tongue design, because it will be immediately adjacent to the outside joint surface where the brazing alloy has been preplaced. The original machined dimensions of the outside tongue and groove diametric surfaces nominally are selected as equal to one-third of the joint wall thickness less than the outside diameter of the assembly; i.e., $D_3 = D_6 = D_2 - \frac{1}{3}\ (\frac{D_2 - D_1}{2}) = D_7 - \frac{1}{3}\ (\frac{D_7 - D_8}{2})$.

Stress analyses have indicated that a tantalum tongue thickness, equal to or greater than one-third of the total wall thickness of that component in the joint area, would result in an advantageous stress distribution condition, subsequent to the brazing operation. Based on this consideration, the inside tongue diameter, at machining, is established as,

$$D_5 = D_6 - (0.4)\ (\frac{D_7 - D_8}{2})\ (2) = D_6 - 0.4\ (D_7 - D_8).$$

The as-machined dimension at the inside of the stainless steel groove is determined by (1) application of the previously indicated expansion equation to both the tongue and groove inside diameters, and (2) including allowances for achieving desired braze capillary spacing at the brazing temperature. Thus, the inside diameter of the tantalum tongue at the brazing temperature is calculated; i.e., D_5 at 2160°F (1182°C) = D_5 original $(1 + \alpha_{Ta}\ \Delta T)$. The inside groove diameter, D_4, at temperature is then equal to that tongue diameter, less twice the desired capillary flow spacing; i.e., D_4 at 2160°F (1182°C) = D_5 at 2160°F (1182°C) - 2 (0.003 inch nominal spacing). The original groove inside diameter to be machined is then established; D_4 original = $\frac{D_4 \text{ at } 2160°F}{1 + \alpha_{ss}\ \Delta T}$.

The axial tensile strength of tongue-in-groove brazed joints is dependent on the braze alloy shear strength and the tensile strength of the joint components. The known low shear strength of the cast J-8400 braze alloy may be compensated for by increasing the length of the tongue and the depth of the groove, L_2 and L_1, respectively in Figure 1, which increases the shear load support area. These dimensions may be increased to a point where the effective shear area is many times the cross sectional area of the joint components. The practical limitation of this compensation is the distance over which the braze alloy must flow during the brazing operation. For any size tubular joint, increases of the tongue/groove lengths, in unit multiples of the wall thickness, produce shear areas which increase by a factor of twice the tube cross section.

Some other comments regarding design configurations are as follows:

1. The difference between the outside diameters of the two component parts (D_2 - D_7) is usually maintained at 0.04 - 0.06 inch to provide an area for braze alloy preplacement and exterior braze fillet formation.

2. The edges of components in the tongue and groove area are rounded to reduce stress concentrations in those areas.

3. The diameters of the stainless steel component, D_1 and D_2, may be varied slightly in the joint area, such that the wall thickness there is greater than at other axial locations. This action permits increasing of the tantalum tongue thickness to a more suitable dimension.

The preceeding discussion indicates most of the considerations which were included in the design of the tantalum/Type 316 stainless steel tubular joints for this study program. The desired overall configuration of the bimetallic assemblies was 2-inch OD by 0.12-inch wall by 6 inches long. The resultant design configuration employed is presented in Figure 2.

MATERIALS AND PROCESSES

The materials and equipment utilized in this investigation are

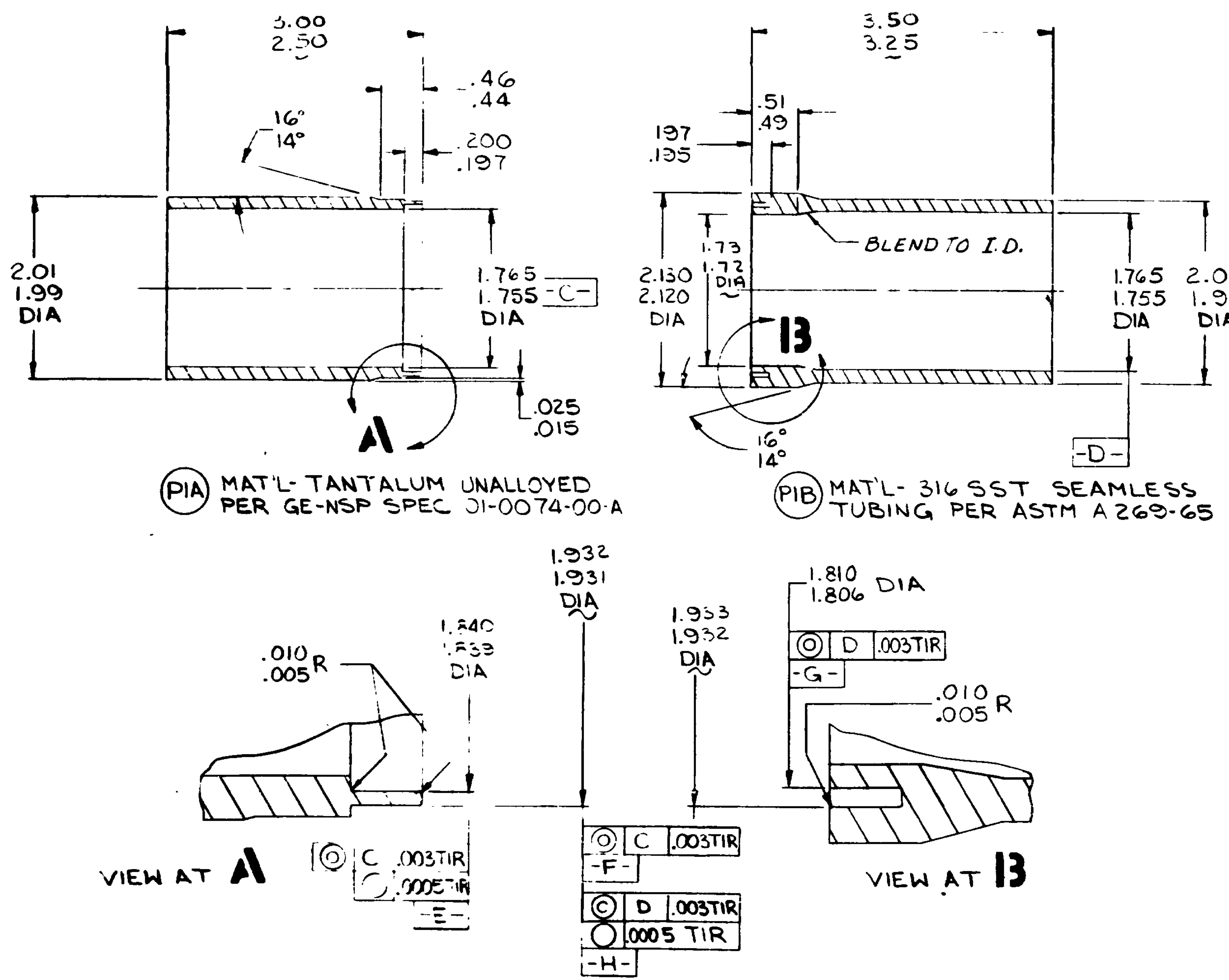


Figure 2. Basic Design Configuration of Brazed Tantalum/Type 316 Stainless Steel Bimetallic Joint.

summarized in the following tabulation:

MATERIALS

1. Unalloyed tantalum tubing - 2 inch OD by 0.12 inch wall
2. Unalloyed tantalum sheet - 0.130 inch thickness
3. Type 316 stainless steel tubing - 2.125 inch OD by 0.188 inch wall
4. Type 316 stainless steel sheet - 0.130 inch thickness
5. J-8400 braze alloy in powder form - per GE Specifications B50T56 and B50T56-S1
6. Brazing aids - Nicrobraz "Cement" and "Green Stop-off"; both are commercial products manufactured by the Wall-Colmonoy Company
7. Reagent grade acetone and ethyl alochol
8. Reagent grade acids - HNO_3, HF, and H_2SO_4
9. Deionized and tap water
10. Platinum - platinum + 10 percent rhodium thermocouple wire 0.020 inch diameter

EQUIPMENT

1. Vacuum furnace - Richard D. Brew Inc. Furnace, Model 424B.
2. Vacuum gauges and readout - Fredericks Inc., "Televac" readout and dual filament ionization gauge.
3. Temperature recorder - Brown Inc. "Electronik", pen line recorder.
4. Potentiometer - Leeds and Northrup Inc., millivolt potentiometer.
5. Emf signal amplifier/readout - Sanborn Inc., preamplifier and two channel readout.
6. Helium leak detectors - General Electric Company and National Research Corporation, Mass Spectrometers.
7. Ultrasonic inspection gear, including a display/timer, pulser/ receiver, gate, high-frequency search units, facsimile recorder and a centering rotational fixture.

MATERIALS PROCUREMENT AND QUALITY ASSURANCE

The tantalum sheet material procured met the compositional requirements of ASTM B 364-62T with reduced maximum allowable interstitial elements content; i.e., oxygen 100 ppm, nitrogen 75 ppm, carbon 50 ppm, and hydrogen 10 ppm. A sample of the as-received tantalum sheet was examined metallographically and found acceptable; a typical microstructure is shown in Figure 3. The tantalum tubing was procured to GE-NSP Specification 01-0074-00-A. Confirming quality assurance samples of the as-received tubing were submitted for in-house metallographic and chemical analyses. All of the tubing was ultrasonically inspected, per GE-NSP Specification 03-0001-00-A. The chemical analysis and microstructural examination confirmed that the tantalum tube material met the indicated specification requirements. A typical microstructure of the as-received tantalum tubing is shown in Figure 4.

The Type 316 stainless steel sheet and tubing were procured to standard ASTM specifications, A240 and A269, respectively. Confirming spectrographic analyses indicated that both lots of material met the specification requirements. Ultrasonic inspection, per GE-NSP Specification 03-0001-00-A, of the stainless steel tubing indicated that it was acceptable for usage. A sample of that material was also examined metallographically, as a further quality assurance measure, and deemed structurally satisfactory; a typical microstructure is shown in Figure 5.

BRAZING

The following general sequential steps were utilized in the preparation and brazing of all sheet samples and the majority of the tubular assemblies.

1. The tantalum and stainless steel sheet and tubing joint components were machined per applicable drawings.

2. (a) Tantalum pieces were cleaned by (1) degreasing with acetone and ethyl alcohol, (2) pickling in a solution consisting of 50 parts HNO_3, 25 parts H_2O, 12.5 parts HF, and 12.5 parts H_2SO_4, by volume, (3) rinsing with tap and deionized water, and (4) air drying.

   (b) Stainless steel pieces were cleaned by degreasing with acetone and ethyl alcohol, followed by a vacuum outgassing treatment at 2000°F (1093°C)/15 minutes.

Etchant 100X

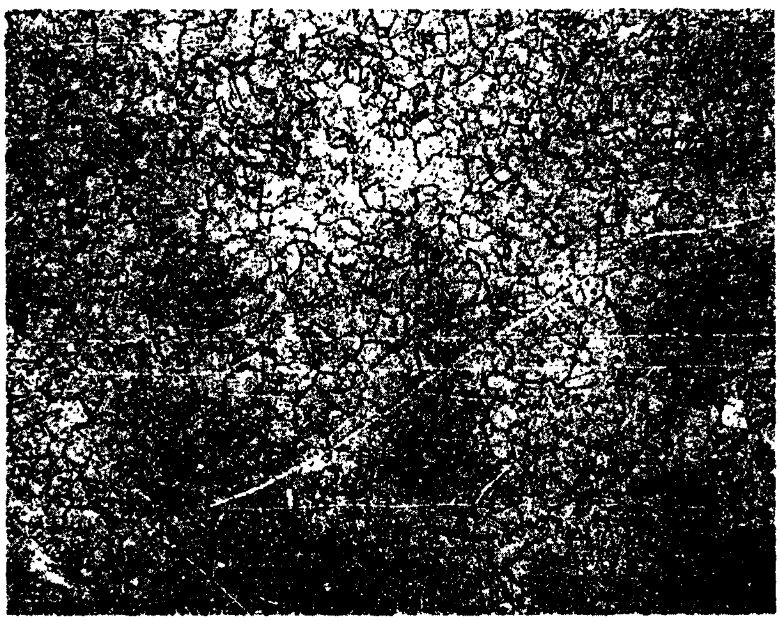
$NH_4-HNO_3-H_2O$

Figure 3. Typical Microstructure of "As Received" Tantalum Sheet. (MB 795A)

Etchant 100X

$NH_4F-HNO_3-H_2O$

Figure 4. Typical Microstructure of "As-Received" Tantalum Tubing. (MB 709A)



Etchant 100X

$HNO_3 + HCl$

Figure 5. Typical Microstructure of "As-Received" 316 Stainless Steel Tubing. (MB 871B)

3. Components were assembled for brazing, using clean, lint-free nylon gloves (tantalum shim stock was used to maintain desired brazing tolerances for the sheet brazed samples).

4. Powdered braze alloy was applied as a slurry to the joint areas of all assemblies, using "Nicrobraz Cement" as a binder/carrier. After waiting a minimum of two hours, to allow initial volatilization of the binder to occur, the joints were ready for brazing. "Stop-off" was applied to the joint surfaces, adjacent to the brazed areas, to prevent braze runoff.

5. Thermocouples (Pt-Pt+10% Rh wires and Al_2O_3 insulators) for temperature measurement, were resistance tack welded to exposed tantalum and stainless steel surfaces at selected locations. Individual wires were attached at their ends only, thereby producing junction thermocouples. Tantalum foil (0.002-inch thickness) was positioned around the thermocouples, not touching the wires, to avoid potential incorrect temperature readings caused by: (1) a change in chemistry of the thermocouple wires as a result of evaporation and subsequent alloying of volatile braze constituents with the thermocouple wire material; and (2) a "fin cooling" effect at the wires between the tack welded junctions and the nearest Al_2O_3 insulator.

6. The instrumented assemblies were positioned in the vacuum furnace, shown in Figure 6, which was then evacuated to a pressure of less than 5×10^{-5} torr before starting the brazing heatup cycles. The tubular joints were brazed in a vertical position with the stainless steel member on the bottom. Thermal heat shielding was positioned, as necessary, around the joint assemblies and at furnace ports.

7. The assemblies were heated to selected brazing temperatures in accordance with the time-temperature schedule presented in Figure 7. The heating cycle consisted of five pertinent zones; i.e., (1) heating to 800°F (427°C) at a relatively slow rate (approximately 50°F (27°C/minute), to prevent "spalling off" of the applied braze powder, (2) holding at 800°F (427°C) to

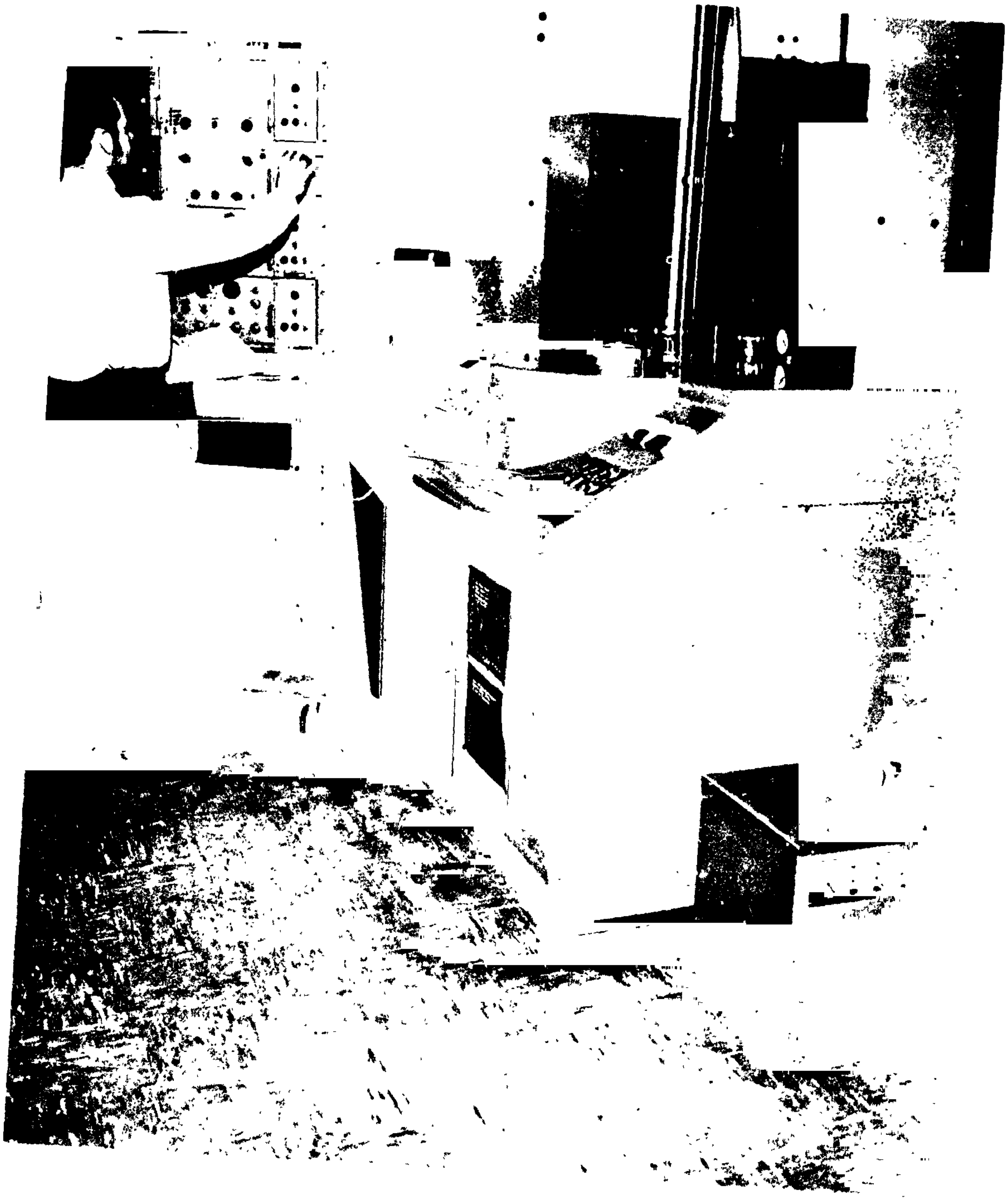


Figure 6. Vacuum Furnace Used in Brazing Operation Shown with Fast Response Millivolt Recorder. (P70-3-1)

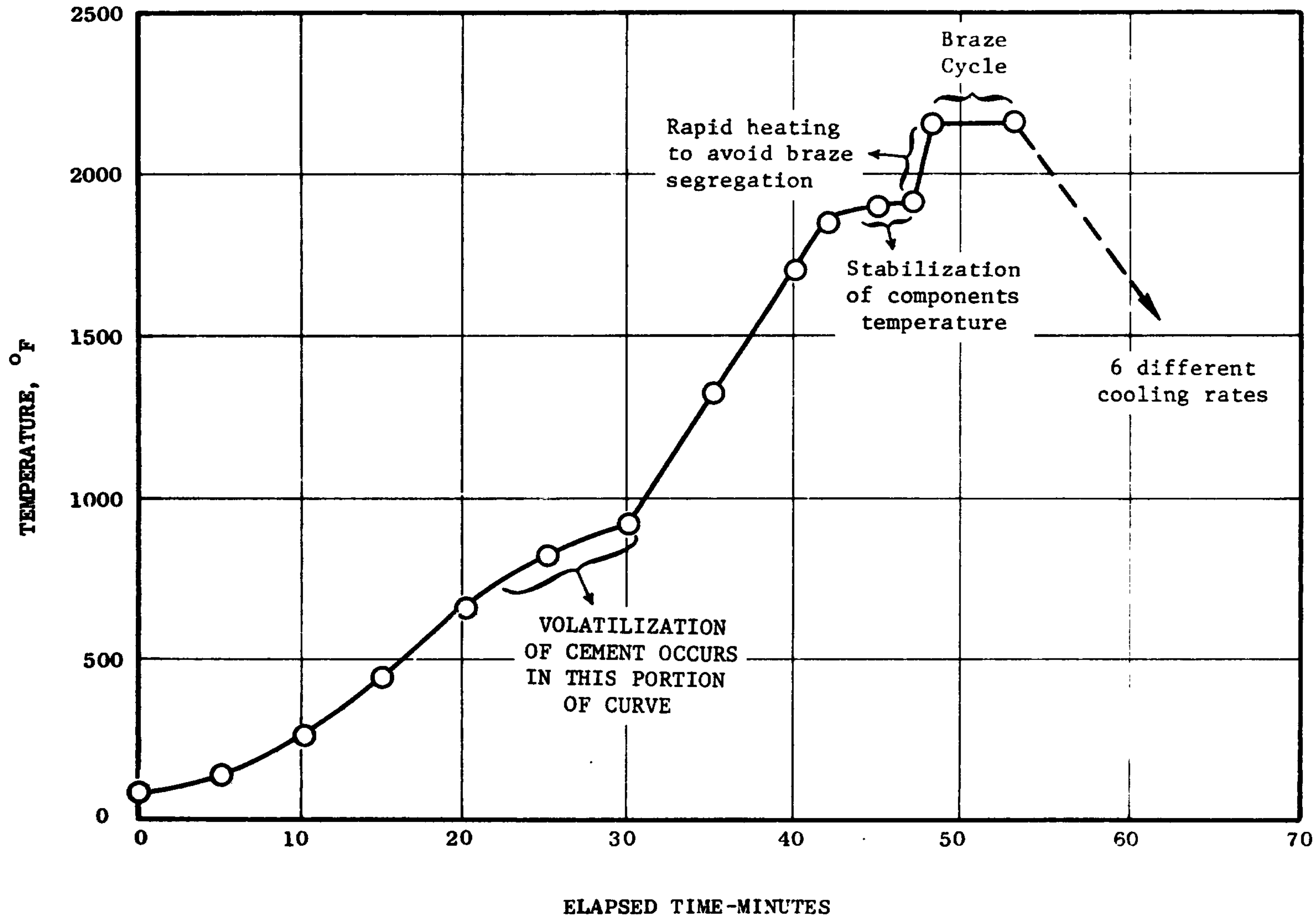


Figure 7. Typical Time-Temperature Schedule for Brazing Operation

allow complete volatilization of the binder to occur, (3) heating at a nominal rate (approximately 70°F (39°C)/minute) to a temperature slightly below the solidus temperature of the J-8400 braze alloy - 1925°F (1052°C), (4) holding at 1925°F (1052°C) to allow stabilization of component temperatures, and (5) rapid heating (approximately 250°F (139°C)/minute) to the brazing temperature to prevent segregation and nonuniform melting of the braze alloy.

8. The assemblies were held at the brazing temperature for a sufficient time, before cooling, to allow the brazing alloy to flow and fill the tongue-in-groove annular braze cavities.

9. The assemblies were cooled in vacuum, from the brazing temperature to 1400°F (760°C) at a predetermined rate, during which time the braze alloy solidified.

10. The assemblies were then cooled at a nominal furnace cooling rate to room temperature, and the thermocouples removed. Residual "stop-off" material was then removed from external joint surface by wire brushing.

11. All assemblies were thereafter ready for inspection and evaluation. The outside braze fillet surfaces of the production joints were machined, after nondestructive testing, to remove excess braze materials from those areas.

The same general technique was employed in the brazing of tubular joints for the directional solidification study with the exceptions of the locations of the instrumentation thermocouples, and the number and location of the thermal shields employed.

POSTBRAZE INSPECTION

After brazing of tubular joints, several nondestructive inspection techniques were employed to determine joint quality. Ultrasonic inspection was the inspection tool of predominant importance used for evaluating joint acceptability.

The ultrasonic equipment used in this investigation consisted of (1) a standard display unit with a special broadband pulser-receiver and a rapid gating system for separate recording of the braze annuli at the inside and outside of the tongue and groove of tubular assemblies, (2) a special transducer, and (3) a rotational fixture which allows both incremental indexing for "C-scan" recording (plan view) and continuous rotation for modified "A-scan" (X-Y) recording. A general ultrasonic test setup is shown in Figure 8. The procedure for attaining "C-scan" recordings of the sheet and tubular tongue-in-groove brazed joints was as follows:

1. The gate was set electronically to isolate one of the braze regions (inside or outside of the tongue and groove).
2. The joint area was scanned axially by a back and forth movement of the pulser-receiver sweep unit.
3. The back and forth motion was repeated after circumferential or transverse indexing to reposition the sweep unit 0.004 inch away from the previous scan position.
4. The entire joint area of a given brazed assembly was inspected by repeating the indexing-scanning operations sufficient times.

An indication of a defect appeared as a black area on the "C-scans", whereas sound-brazed areas appeared white. Different levels of recording pickoff and different sensitivities of inspection were used to display specific defect areas. Thus, defects of all sizes were capable of being shown on a given "C-scan".

The procedure for achieving modified "A-scan" presentations of the tubular tongue-in-groove brazed joints was as follows:

1. The transducer was positioned at the axial extremity of the brazed area.
2. The joint was then rotated under the transducer through 360° and an X-Y recording made of the relative magnitudes of the ultrasonic signals generated. Again the ultrasonic gate was electronically set to isolate the two brazed areas.

Figure 8. Ultrasonic Nondestructive Test Setup. (P69-4-27C)

3. After the initial circumferential scan was completed, the transducer was repositioned 0.010 inch away (axial displacement) from the initial transverse plane of inspection and a second X-Y scan recording obtained.

4. The repositioning-rescanning process was repeated to obtain inspection data for the entire joint; each plane was separated from the previous plane by 0.01 inch.

These modified "A-scans" thereby presented the magnitude of ultrasonic signals versus a specific location in the tubular joints. These scans were utilized in the correlation study phase of this program and for production joint inspection, since they covered a wider range of inspection sensitivities than those generated in the "C-scan" inspections. More detailed descriptions of the ultrasonic techniques and equipment will be indicated in later paragraphs related to actual samples and/or production joint inspection.

After postbraze ultrasonic inspection and machining of the tubular production joints had been completed, all were helium leak tested and dye penetrant inspected as a further check of their quality. Figures 9 and 10 depict the helium leak testing and dye penetrant inspection facilities used for those operations.

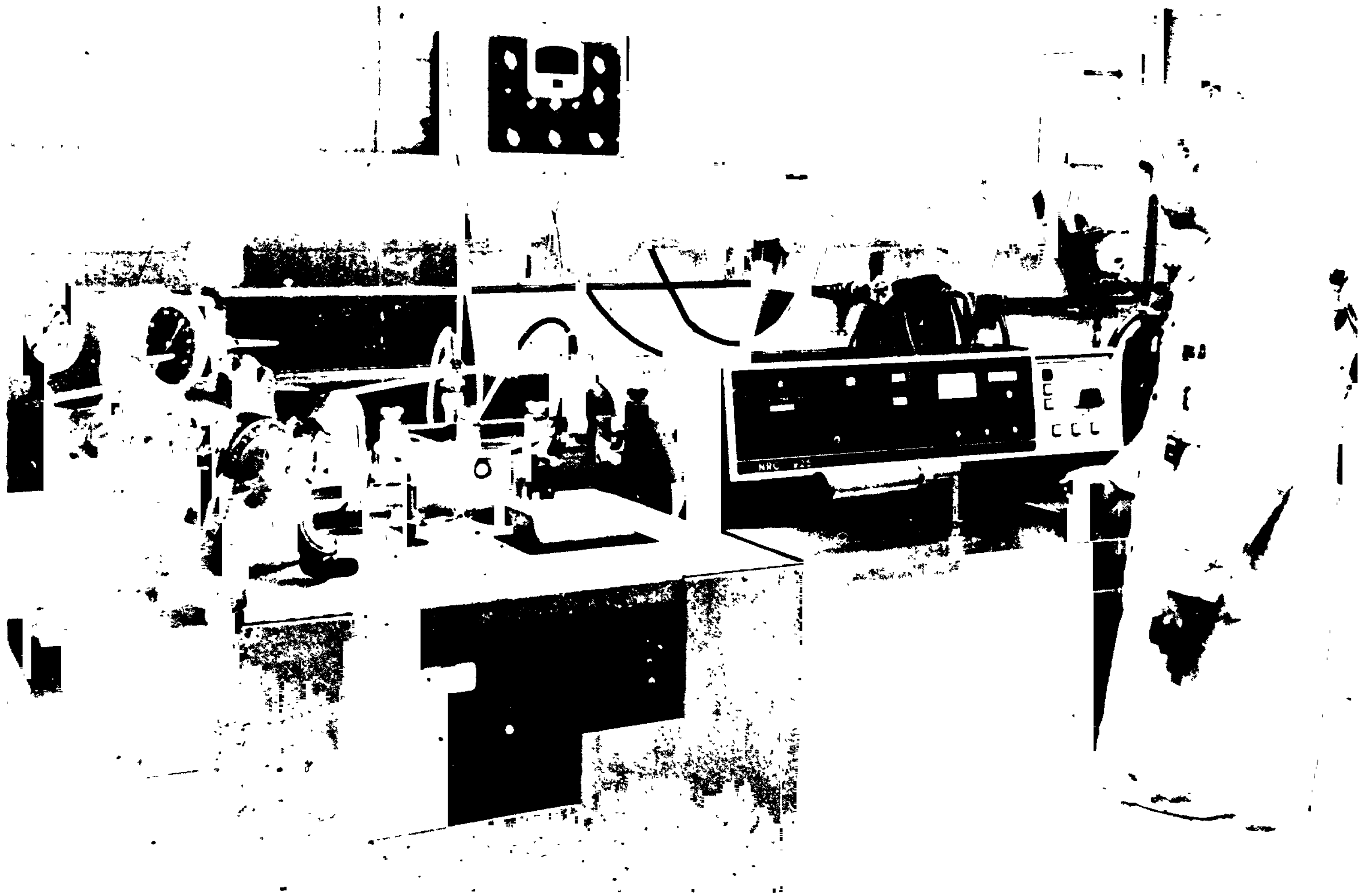
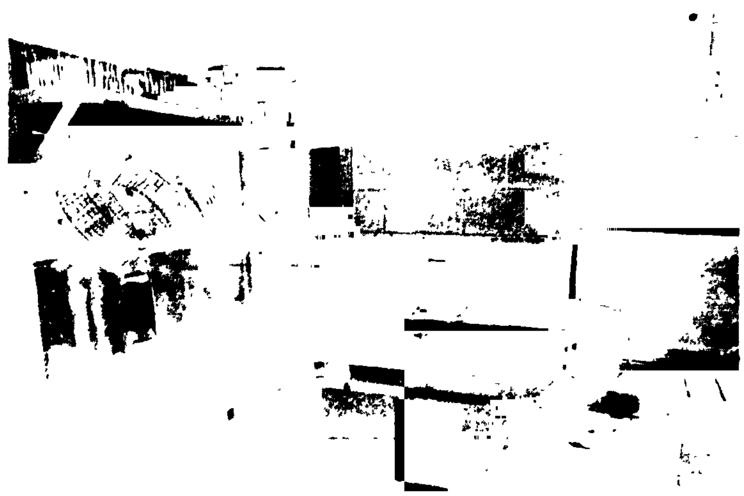


Figure 9. Helium Mass Spectrometric Leak Detection Equipment. (P67-12-27E)



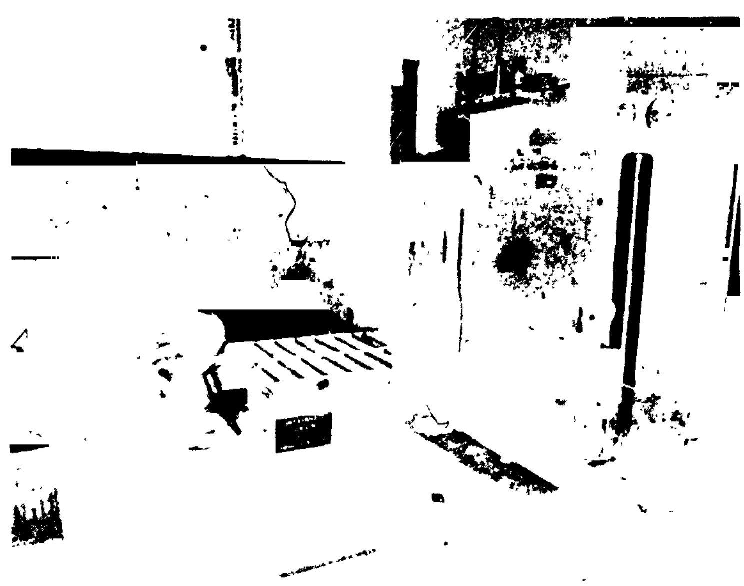


Figure 10. Fluorescent Penetrant Nondestructive Test Station Utilized for Detection of Surface Defects. (Upper, P66-12-19C, Lower P68-12-19B)

III. RESULTS AND DISCUSSION OF RESULTS

BRAZING THERMAL PARAMETER INVESTIGATIONS

Some of the important factors considered in the preparation of brazed assemblies include the following:

1. Melting temperatures of the braze alloys and parent metals.
2. Metallurgical compatibility of the braze alloy with the base metals at the brazing and service operating temperatures.
3. Control of the brazing environment to prevent contamination of the joint constituents and impairment of braze wettability.
4. Metallurgical reactions during the brazing cycle which can produce detrimental effects on the nature of the braze alloy solidification.
5. Assembly design configuration to accommodate differences in components properties.
6. Strength and ductility of fabricated brazements.

Most of these variables, regarding tubular tantalum/Type 316 stainless steel brazed joints, have been previously considered in association with component fabrication for the SNAP-8 Refractory Boiler Development Program.[1,2] The areas requiring further study in this optimization program were concerned with determining the effects of braze cycle cooling rate variations on the solidification characteristics of the J-8400 braze alloy and the corresponding strength properties of representative brazed assemblies.

Brazing may be equated to a casting process, where the metallic filler alloy is the material being cast, and the components being joined form the casting mold. Most metals being cast contract during solidification; such is also true for the freezing of braze alloys. This contraction or shrinkage may result, during nonequilibrium cooling, in the formation of objectionable microshrinkage voids in the last areas of the braze material to solidify. In casting or brazing, the microshrinkage void formation can be minimized by using very slow cooling rates during solidification, which would provide sufficient time for necessary equilibrating diffusion to occur. While an improvement in the braze alloy freezing characteristics can be realized by slow cooling, potentially adverse reactions in the base metals would be magnified. Thus, it is imperative to determine the cooling rate which produces a minimum amount of braze microshrinkage and an acceptable amount of braze-base metal interaction in order to insure brazed assemblies with optimum overall properties.

COOLING RATE STUDY-SHEET SPECIMENS

The effects of cooling rate variations on the extent of J-8400 braze alloy microshrinkage and related base metal penetration diffusion reactions in tantalum/Type 316 stainless steel brazed joints were investigated to establish optimum conditions. Sheet materials, 0.130-inch thick, were employed for this study. Two types of specimens - simple overlap and tongue-in-groove sheet samples - were used, each having dimensions in their joint areas which closely approximated those of tongue-in-groove tubular assemblies. The as-machined configurations of these sheet samples are shown in Figures 11, 12 and 13.

Overlap Specimens Processing and Evaluation

The initial joints prepared were the overlap type. The tantalum and stainless steel component parts of these samples were assembled and vacuum brazed with the J-8400 alloy, using the previously described techniques. Six, 4 t overlap (overlap equals 4X sheet thickness) specimens were individually brazed at 2160°F (1182°C)/5 minutes and subsequently cooled to 1400°F (760°C) using 25°F (14°C), 50°F (27°C), 75°F (42°C), 100°F (55°C), 125°F (70°C), and 150°F (84°C) per minute rates, during which time the braze alloy solidified. Visual examination of the samples, after brazing, indicated good braze flow and wetting over the entire brazed areas.

The brazed overlap specimens were ultrasonically inspected to

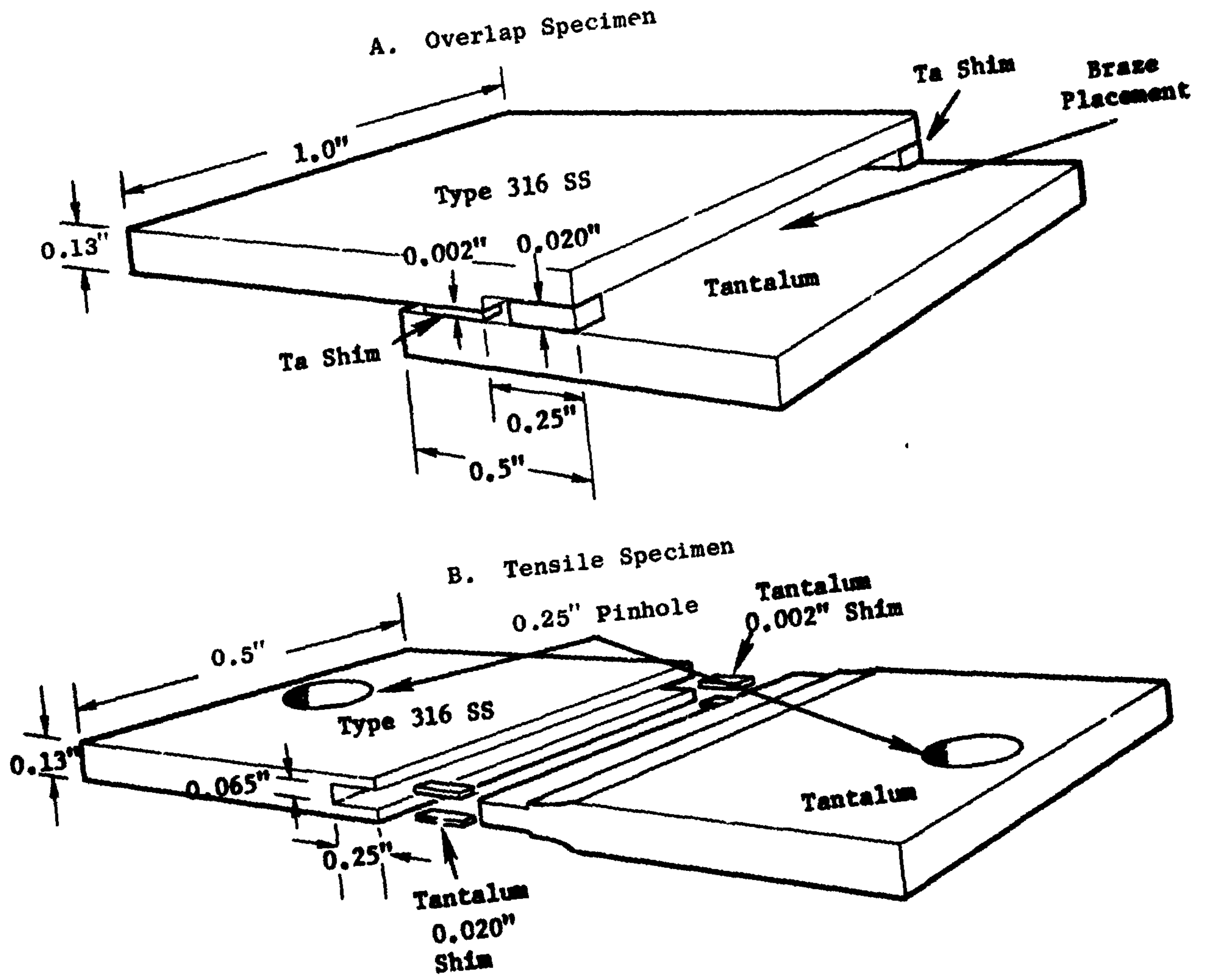


Figure 11. Sketches of Components for (A) Overlap and (B) Tensile Specimens for Cooling Rate Study.

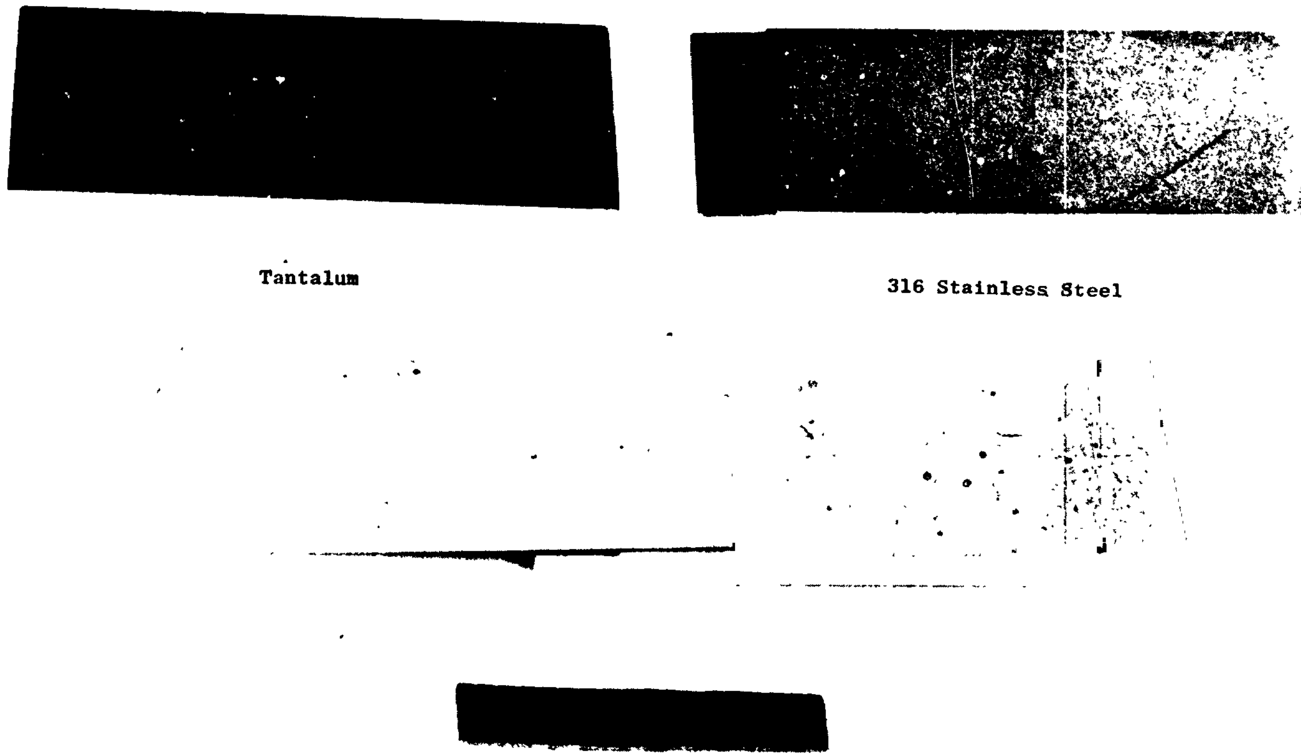


Figure 12. As-Machined Sheet Overlap Specimens. (P69-4-43B)

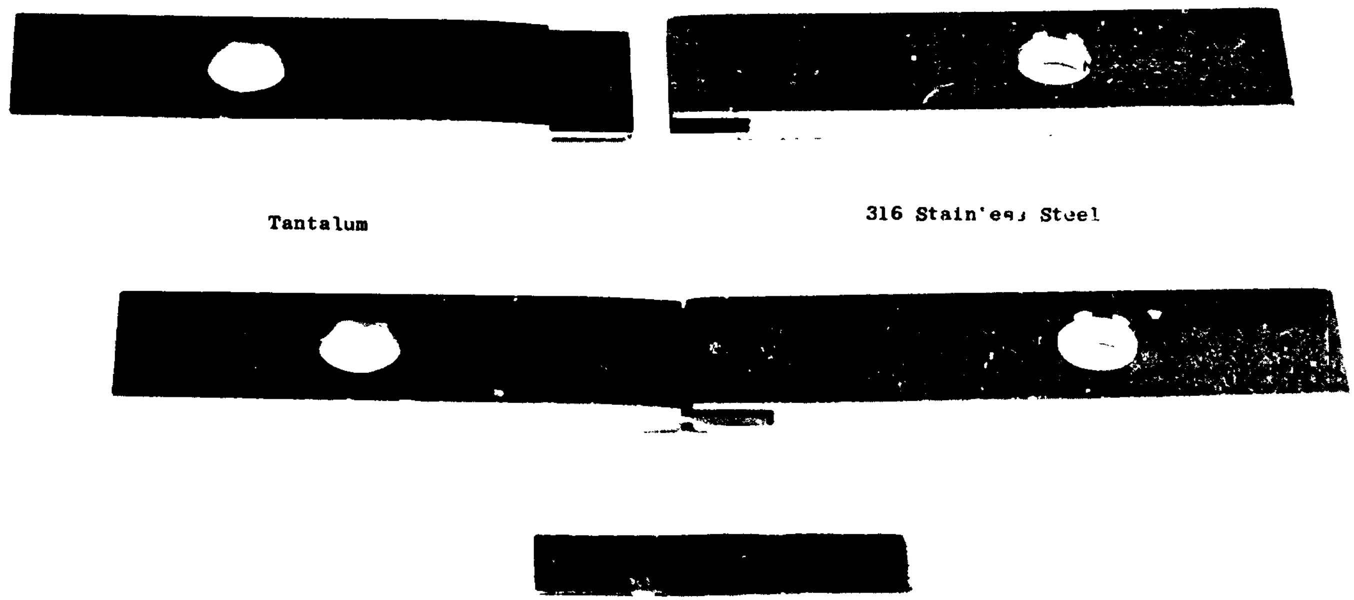


Figure 13. As-Machined Tongue-in-Groove Sheet Tensile Specimens. (P69-4-43A)

determine the comparative braze quality of each. Appropriate areas for metallographic examination were selected from the generated ultrasonic scans. The areas chosen were representative of the most significant ultrasonic defect indications for each sample, rather than arbitrary sections through the brazed areas. This was necessary because a well defined ultrasonic standard was not available for use during their inspection. The purpose of the metallographic examination was twofold: i.e., first, to establish the capability of the ultrasonic inspection "C-scan" presentations for accurately depicting defects (microshrinkage voids) in the brazed areas; and second, to determine the extent of braze-base metal interactions relative to a particular cooling rate. The data from the ultrasonic-metallographic examination were then used to select the cooling rates to be used in further assemblies brazing. The following paragraphs will describe the ultrasonic inspection technique and equipment used in examination of the overlap specimens.

The ultrasonic inspection was performed using a high resolution, linear response ultrasonic system. That system employed a high-frequency (25 MHz) transducer and a broad-band pulser-receiver with pulse duration in the nanosecond (10^{-9}) range. The short pulse duration enhanced the ability to separate (resolve) individual defects, while the high frequency provided the capability for detection of smaller defects. The ultrasonic beam was focused to a point approximately 20 mils in diameter at its focal point in water and possibly to an even smaller diameter in the assemblies being inspected. Thus, the ultrasonic system used had the inherent capability for detecting very small (approximately 1 mil) voids or defects.

Interference with the ultrasonic beam by grain boundaries, metal-metal interfaces and abrupt material changes reduced the actual detection level below that of the inherent capability. An additional goal of this phase of the study program was to determine what the actual detection capability of the described ultrasonic system was for a brazed joint where one brazed area must be penetrated to inspect a second brazed region, as in the tongue-in-groove design configuration. Defects encountered in the first braze tend to reduce the capability of detection in the second braze. Thus, the inspection data for the overlap specimens was subsequently compared with the ultrasonic results for the tongue-in-groove sheet tensile specimens, indicated later, to determine any differences in detection capabilities when a brazed area separated from the sonic beam entry surface by a second braze layer was inspected.

Since no standard was available for use in setting proper sensitivity levels, a natural defect in a spare overlap sample (in which braze filling was incomplete) was used for calibration. When a medium sensitivity setting on this natural defect was used, several defect indications were noted in the "C-scan" (plan view) recording of the spare specimen. However, almost the entire joint area of that specimen appeared to contain defects, which masked the natural defect, when a maximum sensitivity level of inspection was employed. Thus, the medium sensitivity level was selected for inspection of the overlap joints, and the resultant scans used to pick the areas for metallographic inspection. The samples were sectioned, at the desired inspection location, generally parallel to the long axes of the specimens (refer to Figure 11) and processed to examine those planes.

Microstructural examination of the overlap specimens at the ultrasonically selected areas was performed and detailed maps were generated to pictorially show the cross sections of the individual samples. Primary emphasis was placed on noting the size and distribution of the microporosity present in the braze areas, since those voids were expected to have caused the ultrasonic indications. The prepared maps were compared directly with the ultrasonic "C" scan presentations and generally good agreement noted. All "lack of bond" zones indicated by ultrasonics were found, as expected, to be associated with microshrinkage porosity. Further, individual voids, less than 0.002-inch diameter, were not indicated by the ultrasonic scans. Subsequent inspection and comparison of the overall ultrasonic scans for each specimen indicated that minimum braze microshrinkage was related to slower cooling rates; faster rates produced either larger bulk void areas or more numerous microvoids, primarily found in the wide gap (0.020-inch spacing) sides of the specimens.

It was also observed that the voids had formed predominantly in the solidified J-8400 braze alloy immediately adjacent to the braze-stainless steel interfaces, indicating that the last solidification to occur was in those zones.

The 25°F (14°C)/minute and 150°F (84°C)/minute cooling rates produced the minimum and maximum braze microshrinkage voids, respectively. Since the primary goal of the cooling rate study, however, was to determine the rate which would produce joints having optimum overall characteristics, it was also necessary to consider factors other than braze microshrinkage. These factors included (1) depth of braze constituent penetration into the stainless steel, (2) extent of intermetallic phase formation at the braze/tantalum interface, and (3) ductility or hardness of the parent metals and solidified braze materials. Cooling rates which favored minimum braze microshrinkage were expected to increase the extent of these potentially detrimental braze/parent metal interactions. If such were the case, some intermediate cooling rate from the brazing temperature might actually be superior overall to the 25°F (14°C)/minute rate. Additional microstructural examination and supporting microhardness testing were performed to establish the relative effects of the various cooling rates on the above described factors.

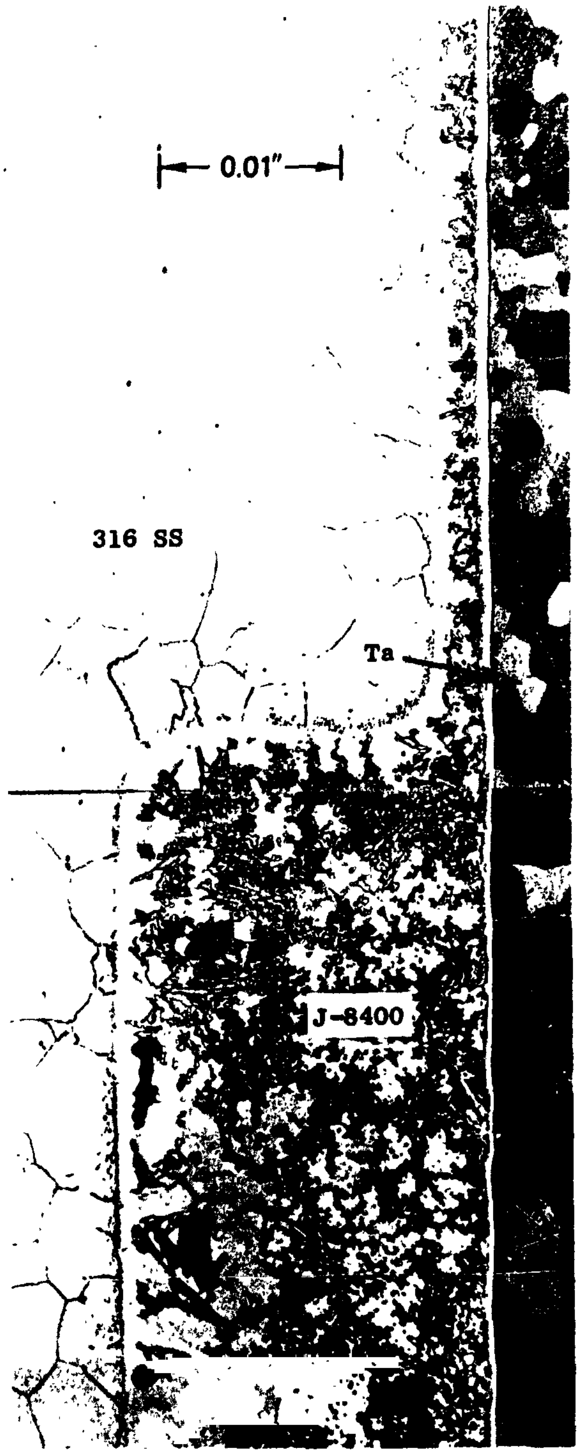
The depth of braze constituents penetration into the stainless steel of the overlap specimens, during brazing, was qualitatively measured by metallographic examination. The results of those measurements are presented in the following tabulation:

Specimen Cooling Rate from 2160°F (1182°C) to 1400°F (760°C)	Depth of Penetration in Stainless Steel	
	Wide Gap Side	Narrow Gap Side
(°F/minute)	(inches)	(inches)
25	.0137 - .0145	.0102 - .0115
50	.0123 - .0131	.0097 - .0108
75	.0108 - .0117	.0092 - .0104
100	.0095 - .0105	-
125	.0101 - .0106	-
150	.0090 - .0104	.0076 - .0084

The measurements were made in the stainless steel 0.020 to 0.030 inch on each side of the right angle step which marked the transition from the wide to narrow braze region in each overlap specimen. The observed penetration into the stainless steel was intergranular in nature. The extent of penetration was measurable because of preferential attack of those intergranular areas by the acids used in metallographic etching of the polished cross sections. As the above data show, greater penetration was associated with slower cooling from the 2160°F (1182°C) braze temperature, although overall variations were slight; i.e., penetration at the wide gap side for the 25°F (14°C)/minute and 150°F (84°C)/minute rates were $\sim$ 0.014 inch and $\sim$ 0.010 inch, respectively. The intermetallic phase, formed at the tantalum/braze interface during brazing, varied in thickness from 0.0015 inch to 0.0005 inch for the 25°F (14°C)/minute and 150°F (84°C)/minute cooling rates, respectively. Figures 14 and 15 depict representative microstructures of the stainless steel-braze-tantalum interfaces of the overlap specimens cooled at 25°F (14°C)/minute and 150°F (84°C)/minute rates, and show the extent of the indicated braze-base metals reactions. These data indicated that more rapid cooling rates would be advantageous for minimizing the possibly detrimental braze/base metal reactions. The benefits derived, however, did not appear to proportionately offset accompanying increases in microshrinkage formation encountered with the more rapid cooling.

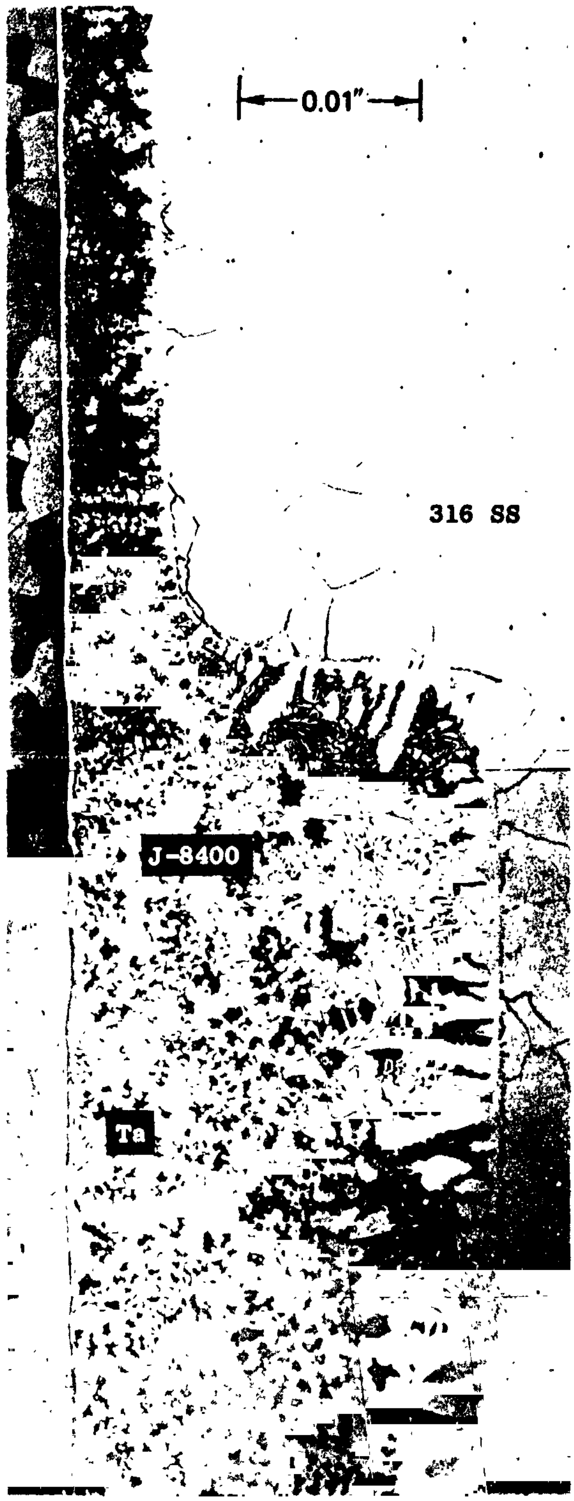
To provide a quantitative measure of the effects of cooling rate variations on the ductility of brazed tantalum/Type 316 stainless steel assemblies, hardness traverses were made across the overlap specimens cooled at 25°F (14°C)/minute and 150°F (84°C)/minute. The tests were performed on both the wide and narrow gap portions of those specimens. The results of these hardness determinations are presented graphically in Figures 16 through 19. A sketch of a full section view of a typical overlap sample is shown on each graph. The dashed line through the sketch in each figure shows the location of the hardness traverse line for each specimen. The data indicated slight hardness increases in the stainless steel-braze penetration zones, as compared with the values obtained in the stainless steel remote (0.05 inch) from the braze area (Kn 190 vs. Kn 160).* The somewhat smaller hardness gradients in the stainless steel of the slow cooled specimen reflects the occurrence of

* Kn = Knoop Hardness Number



100X
Etchant: $NH_4F-HNO_3-H_2O$

Figure 14. Microstructures of Ta/Type 316 Stainless Steel Overlap Braze Specimen Cooled at 25°F/Minute from 2160°F to 1400°F. (Top MB 821A, Bottom MB 821B)



100X
Etchant: NH_4F-HNO_3-H_2O

Figure 15. Microstructure of Ta/Type 316 Stainless Steel Overlap Braze Specimen Cooled at 150°F/Minute from 2160°F to 1400°F. (Top MB 820A, Bottom MB 820B)

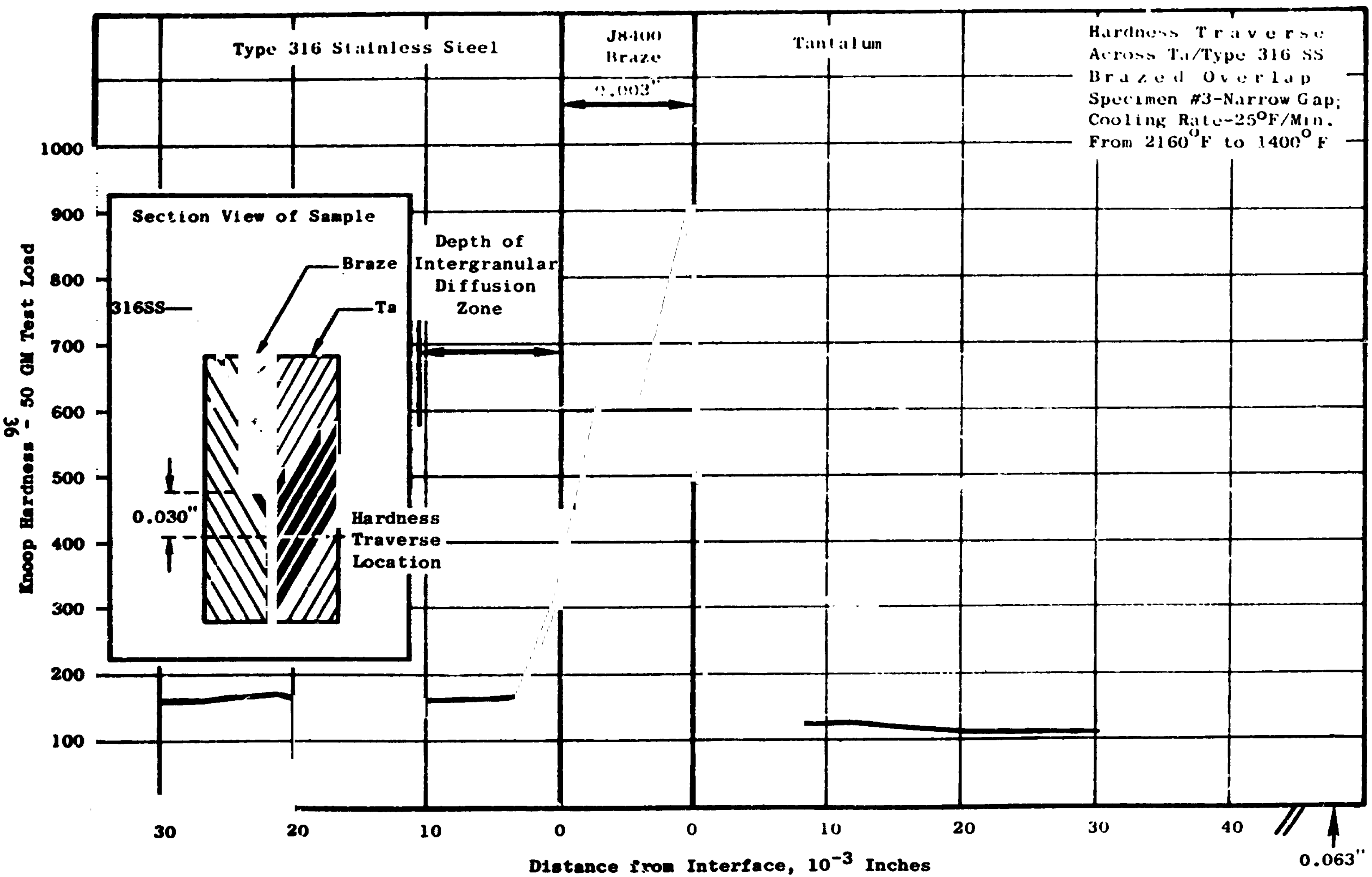
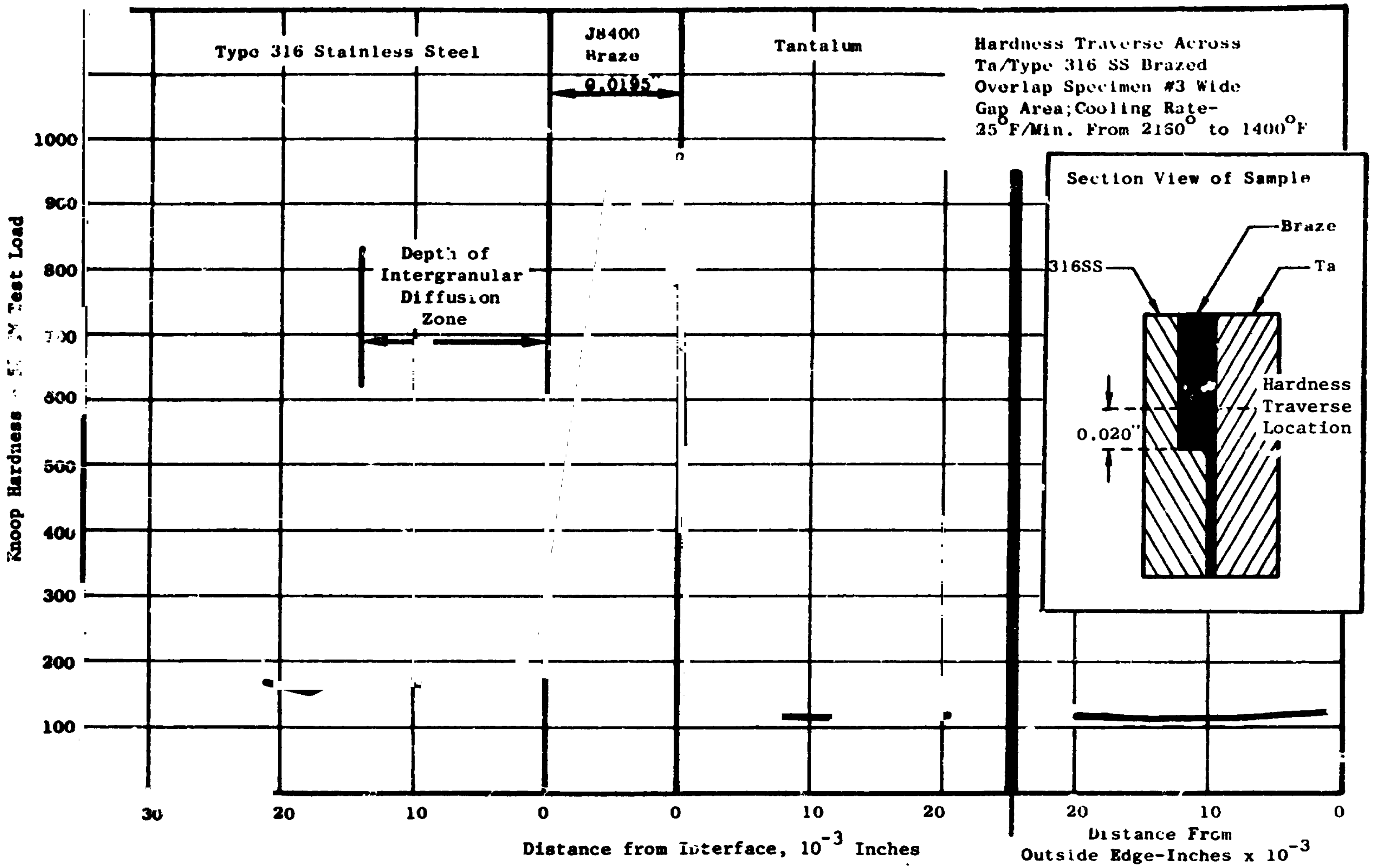

Type 316 Stainless Steel
J8400
Braze
0.003"
Tantalum
Hardness Traverse
Across Ta/Type 316 SS
Brazed Overlap
Specimen #3-Narrow Gap;
Cooling Rate-25°F/Min.
From 2160°F to 1400°F
Section View of Sample
Braze
316SS
Ta
0.030"
Hardness
Traverse
Location
Depth of
Intergranular
Diffusion
Zone
Knoop Hardness - 50 GM Test Load
1000
900
800
700
600
500
400
300
200
100
30
20
10
0
0
10
20
30
40
0.063"
Distance from Interface, 10^-3 Inches

Figure 16.



Typo 316 Stainless Steel
J8400 Braze
0.0195"
Tantalum
Hardness Traverse Across Ta/Type 316 SS Brazed Overlap Specimen #3 Wide Gap Area; Cooling Rate-25°F/Min. From 2150° to 1400°F
Section View of Sample
Braze
316SS
Ta
Hardness Traverse Location
0.020"
Depth of Intergranular Diffusion Zone
1000
900
800
700
600
500
400
300
200
100
Knoop Hardness - Test Load
30
20
10
0
0
10
20
20
10
0
Distance from Interface, 10^{-3} Inches
Distance From Outside Edge-Inches x 10^{-3}

Figure 17.

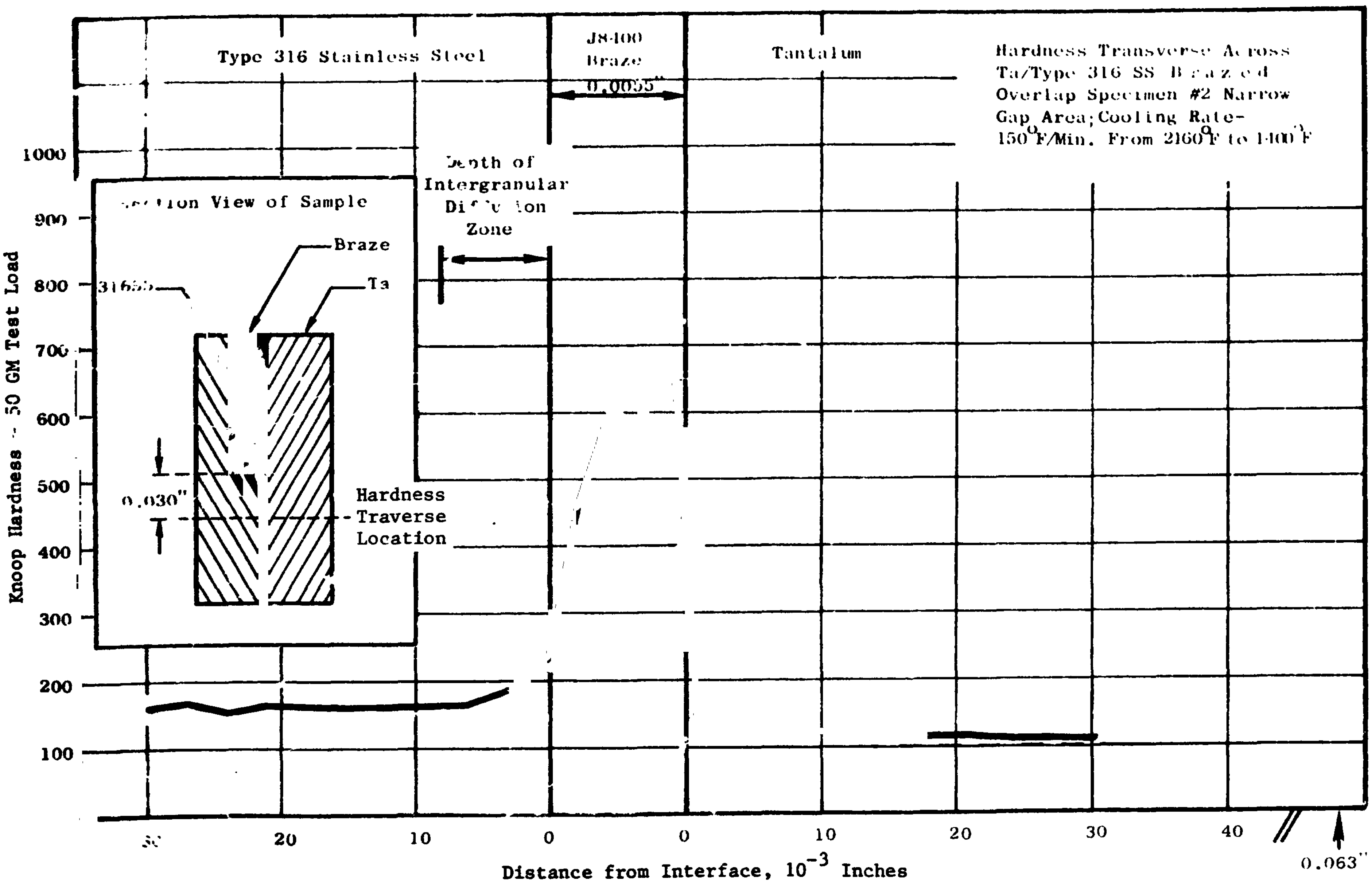
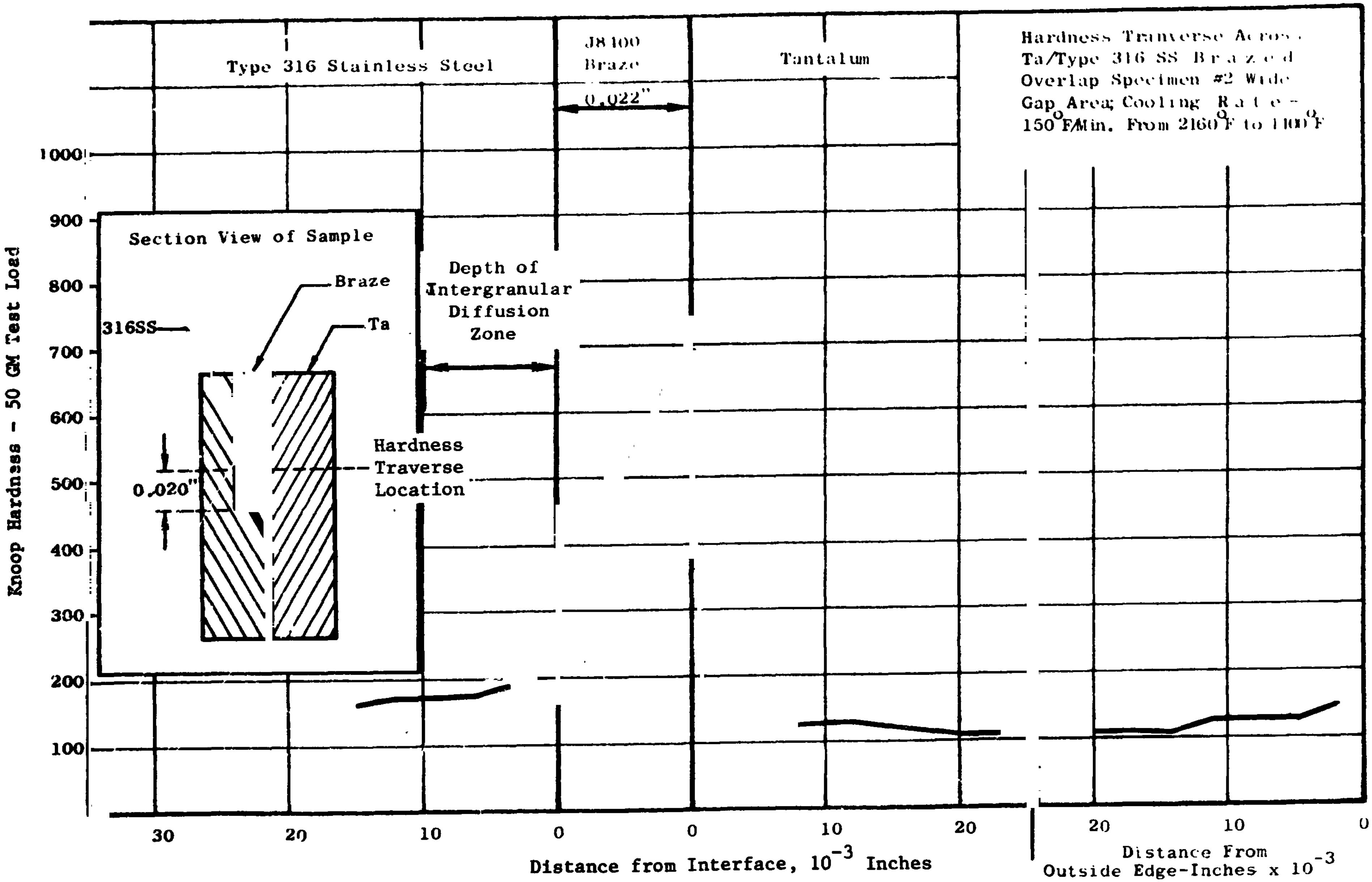

Type 316 Stainless Steel
J8400
Braze
0.0055"
Tantalum
Hardness Transverse Across
Ta/Type 316 SS Brazed
Overlap Specimen #2 Narrow
Gap Area; Cooling Rate-
Depth of
Intergranular
Zone
View of Sample
Braze
Ta
0.030"
Hardness
Traverse
Location
1000
900
800
700
600
500
400
300
200
100
Knoop Hardness - 50 GM Test Load
20
10
0
0
10
20
30
40
0.063"
Distance from Interface, 10^{-3} Inches

Figure 18.



Type 316 Stainless Steel
J8100 Braze
0.022"
Tantalum
Hardness Traverse Across Ta/Type 316 SS Brazed Overlap Specimen #2 Wide Gap Area; Cooling Rate - 150°F/Min. From 2160°F to 1100°F
Section View of Sample
Braze
Ta
316SS
0.020"
Hardness Traverse Location
Depth of Intergranular Diffusion Zone
Knoop Hardness - 50 GM Test Load
1000
900
800
700
600
500
400
300
200
100
30
20
10
0
0
10
20
20
10
0
Distance from Interface, 10^{-3} Inches
Distance From Outside Edge-Inches x 10^{-3}

Figure 19.

some homogenization caused by the longer high temperature exposure of that specimen. The results also show that the formation of the intermetallic phase at the braze/tantalum interfaces effectively minimized further diffusion between the braze and tantalum once the phase had been formed; thus, the sudden hardness decrease in the tantalum only 0.001 inch from the interfaces. The hardness variations found in the tantalum were attributed to variations in the prior cold work at the surface and center of the tantalum sheet material. Similar hardness values were obtained in the tantalum near the tantalum-braze interface and on the outside tantalum surfaces remote from the brazed areas. Higher hardnesses were detected in the J-8400 braze alloy of the slow cooled overlap specimen, as compared with the data for the rapidly cooled sample. This behavior was unexpected, since the longer time, associated with slower cooling, tended to allow more interdiffusion to occur; thus lower hardnesses were anticipated in the braze of the slower cooled specimen. A possible cause for the observed results may have been related to (1) the light load (50 grams) used in hardness testing, (2) the inherent high hardness of the solidified braze (Kn 500-960), and (3) chemistry variation in the braze. The hardness impressions were very small and could have been significantly affected by the specific locations at which the readings were taken. Additional hardness testing was conducted in the brazed areas of the two overlap specimens, using greater loads (200 grams) and numbers of impressions, to provide more representative sampling and clarify the situation. The narrow gap side of the braze of the specimen cooled at 25°F (14°C)/minute had a hardness lower than that of the specimen cooled at 150°F (84°C)/minute. For the wide gap side of the braze, the situation was reversed. A greater number of small microvoids (~ 0.0001 inch) were present in the wide gap area of the specimen cooled at 150°F (84°C)/minute than in the same area of the specimen cooled at 25°F (14°C)/minute and made reliable readings difficult. Thus, determining the effects of the cooling rates, by means of hardness comparisons, was based on data for the narrow gap side of the joints.

In summary, the metallographic examinations of penetration depths and hardness testing data for the overlap braze specimens indicated a slight advantage in using a more rapid cooling rate from the 2160°F (1182°C) brazing temperature. However, the lesser braze microshrinkage, obtained by using a slower rate, was considered to be the most significant beneficial factor because of the relatively low ductility of the J-8400 braze alloy. Thus, a 25°F (14 °C)/minute cooling rate, from the brazing temperature to 1400°F (760°C), was tentatively selected as the optimum rate. This cooling rate, and the 150°F (84°C)/minute rate were then used in the preparation of "proof" tensile specimens.

Tensile Specimens Processing and Evaluation

Six tongue-in-groove tensile specimens were brazed using 25°F (14 °C)/ minute (three specimens) and 150°F (84 °C)/minute (three specimens) cooling rates from the 2160°F (1182°C) braze temperature. Small pieces of tantalum shim stock (0.02 inch and 0.002 inch thicknesses) were positioned in the tongue and groove areas of all six specimens, prior to brazing, to produce brazing gaps equal to those present in tubular 2-inch OD, tongue-in-groove, tantalum/Type 316 stainless steel brazed joints. All six were subsequently inspected by ultrasonic techniques. Those inspections revealed that the faster cooling rate had produced more porosity, as expected from earlier data for the overlap brazed specimens. Metallographic verification of the microporosity present in representative samples from each group was postponed until completion of actual tension testing. The edges of the samples were ground in the joint areas to remove the shim stock, which, if present, could have produced substantial effects on the apparent strength of the assemblies.

The initial tensile test specimen (cooling rate from 2160°F (1182°C) - 150°F (84°C)/minute) was loaded until failure in the J-8400 braze occurred; a testing temperature of 2050°F (1121°C) was necessary to induce the failure. The results of the initial specimen (#5) tensile testing are summarized in Table I. As indicated in the table, the specimen had been stressed at 1850°F (1010°C), 1900°F (1038°C), 1950°F (1066°C), and 2000°F (1093°C) previously, until yielding of the parent metals was observed. The testing, conducted in a vacuum environment, was visually

TABLE I

RESULTS OF ELEVATED TEMPERATURE VACUUM TENSILE TESTING OF INITIAL TONGUE-IN-GROOVE TANTALUM/TYPE 316 STAINLESS STEEL SHEET BRAZED JOINT (SPECIMEN #5)

Test Temperature(1)		Maximum Applied Load(2)		
(°F)	(°C)	(pounds)	(psi)	
1850	1010	390	12,000	
1900	1038	283	8,700	
1950	1066	260	8,000	
2000	1093	243	7,480	
2050	1121	218	6,720	Braze failed

(1) Testing was conducted in vacuum ($< 5 \times 10^{-5}$ torr).

(2) Crosshead travel speed was 0.005 inch/minute; stresses are based on nominal cross section of base materials.

monitored to determine the initial failure location and the propagation path. The visual observation indicated that the eventual failure started in the J-8400 braze at the top of the tongue and groove on the wide gap side of the joint. The failure progressed from there, through the braze and subsequently through the stainless steel at the root of the groove. The solidus temperature on initial heating, for the J-8400 braze alloy in contact with Type 316 stainless steel, has been previously observed as 2000°F (1093°C). The tensile test temperature of 2050°F (1121°C) was required to cause braze failure because interactions of the braze with the parent metals during the lower temperature tests had taken place, thereby changing the characteristics of the braze material present. Because of this phenomenon, a test temperature of 2000°F (1093°C), rather than 2050°F (1121°C), was selected for the remaining tongue-in-groove tensile specimens.

Three additional specimens were tested at 2000°F (1093°C) in vacuum. The specimens were loaded until failure was observed. The results of the additional testing are presented in Table II. The results demonstrated the good load carrying capabilities of tongue-in-groove brazements at 2000°F (1093°C). Since catastrophic failure of the braze occurred in only one test specimen, significant comparisons of the strength data, to assist in selection of a superior brazing cooling rate, was inappropriate. Also, testing of the remaining two joints was abandoned because of the inconclusive nature of the previously generated results.

Ultrasonic inspection of tensile joints before and after testing was performed to determine whether certain defects propagated and to determine the extent of cracking from the edges after test. The primary procedure used was C-scan recordings at more than one sensitivity. On some of the joints an expanded scale C-scan presentation was used where the dimensions on the recording were two or more times those on the actual part. Metallographic examination of specimens #3 and #6 was made after tensile testing to show both the nature of defects present which survived the tensile test and to show the extent of edge cracking, which the posttest ultrasonic examination indicated, did not extend very far (~ 0.010 inch) into the specimens. The metallographic examination confirmed the ultrasonic findings.

TABLE II

RESULTS OF 2000°F VACUUM TENSILE TESTING OF
TONGUE-IN-GROOVE TANTALUM/TYPE 316 STAINLESS STEEL
SHEET BRAZED JOINTS

Specimen Number	Cooling Rate From 2160°F to 1400°F During Brazing	Maximum[1] Applied Load	Maximum[2] Applied Stress	Failure Location/ Mode
	(°F/minute)	(pounds)	(psi	
1	25	211	6500	(3)
3	25	297	9140	(4)
6	150	320	9850	(5)

(1) Crosshead travel speed was 0.005 inch/minute.

(2) Stresses based on nominal cross section of specimens in joint area (0.25 inch x 0.130 inch).

(3) Failure initiated in braze on one side of tongue and groove and progressed from there through the stainless steel at the base of the groove.

(4) Failure occurred through the stainless steel at the base of the tongue and groove; no braze failure was noted; extensive deformation was observed in the stainless steel near the brazed area before failure.

(5) Failure occurred through the stainless steel at the base of the tongue and groove; some cracking of the braze was noted at the surfaces.

The major significance of these results was that the solidified J-8400 braze alloy had the ability to stop edge crack propagation at 2000°F. The braze material in the remaining sections of the specimens was apparently unaffected by the test exposures. The solidification characteristics of the J-8400 braze alloy in the tongue-in-groove tensile specimens was established by means of the metallographic inspection of specimens #3 and #6. Those inspections revealed that lesser braze microshrinkage was present in the specimen cooled at 25°F (14°C)/minute than in the one cooled at 150°F (84°C)/minute, which confirmed that the desired conditions for evaluation were present in the prepared samples.

Summarizing, the essential purpose of the tensile testing of the tongue-in-groove sheet brazed samples was to determine whether varying quantities of defects (microshrinkage voids) in the J-8400 braze would proportionately reduce the shear load carrying capabilities of tantalum/ Type 316 stainless steel brazed assemblies. The primary conclusions reached were (1) the solidified braze alloy could have major void areas, equal to 25 percent of the total brazed area, and still withstand stresses at 2000°F (1093°C) that would cause failure of the stainless steel components; (2) the braze material had the ability to stop propagation of cracks present at its surfaces; (3) redesign of the test samples would be required to yield assemblies completely susceptible to failure through the solidified braze alloy; (4) employment of such redesigned braze specimens would be necessary to provide meaningful data on the effects of microshrinkage on the shear load carrying capabilities of brazed tantalum/ Type 316 stainless steel assemblies; and (5) a clear selection of an optimum cooling rate based on the tensile test results alone was not possible.

THERMAL SHIELDING STUDIES - TUBULAR ASSEMBLIES

The results of the cooling rate study, with sheet tantalum/Type 316 stainless steel brazed samples, indicated that the utilization of a slow rate (25°F (14°C)/minute) during solidification of the J-8400 braze alloy yielded assemblies having optimum characteristics; i.e., minimum braze microshrinkage and acceptable braze-base metal interactions. That basic technique (braze at 2160°F (1182°C)/5 minutes, cool at 25°F (14°C)/minute

1400°F) was employed in the fabrication of the initial tantalum/Type 316 stainless steel tubular production joints (S/N 1 through 10 and S/N 15).

Postbraze ultrasonic inspection of these assemblies revealed that the concentration of braze microshrinkage varied from joint to joint. The minimal extent of microshrinkage in some joints made them acceptable as production joints, while the degree of void formation in others dictated their usage as either ultrasonic standards or correlation study specimens. Additional processing refinements were decided to be required to reduce the quantity, or affect the position, of the braze microporosity. Therefore, two potentially beneficial variations in the brazing technique for tubular assemblies were considered. The variations basically involved adjustments of the thermal shielding used in order to (1) induce directional solidification of the braze alloy during cooling of assemblies from the brazing temperature, and (2) produce a desired temperature distribution radially across the tongue-in-groove area during brazing. Both of these process refinements were investigated by the preparation of additional tubular, tongue-in-groove assemblies, as indicated in following paragraphs.

Directional Braze Solidification

A potential refinement of the brazing process was explored as a possible means of improving the quality of brazed tantalum/Type 316 stainless steel tubular transition joints. The basic technique variation may be described as directional braze solidification. That condition in tongue and groove braze joints could be attained by the initiation of freezing of the J-8400 braze alloy at the base of the stainless steel groove and then forcing the solidification to progress toward the top of the tongue and groove where the braze alloy had been preplaced. Various methods for achieving that goal were entertained, including: (1) moving the assembly being brazed out of the furnace hot zone at a controlled rate and direction, (2) using a movable induction heating coil to maintain desired transient temperature profiles during cooling, (3) positioning of a heat retaining mass inside the tubular tantalum joint components, and (4) positioning of heat shielding around the tantalum joint components to reduce radiant heat losses from that member during cooling from the 2160°F (1182°C) brazing temperature. The latter method was selected for evaluation because it was most readily adaptable to the basic vacuum brazing furnace setup.

Some of the variables requiring evaluation for exploring the heat shielding method to achieve directional solidification were (1) the extent and configuration of heat shielding around the joint, (2) the position of the joint in the vacuum furnace, (3) the effects of presence of braze in the tongue and groove joint area, (4) the basic furnace heat shielding, and (5) the basic furnace cooling rate. These variables were systematically investigated to determine their individual and cumulative effects. The general technique consisted of (1) heating a representative tantalum/ Type 316 stainless steel, tongue-in-groove, tubular joint, having the configuration shown in Figure 2, to the 2160°-2180°F (1182°-1193°C) brazing temperature in vacuum; (2) measuring the steady state temperatures on the outside surfaces of the assembly at several preselected positions in the joint area; and (3) determining the interrelated cooling rates at those positions while reducing the nominal temperature of the assembly to below the solidus temperature of the J-8400 braze alloy. The thermocouple (Pt-Pt+10% Rh) measuring positions, schematically shown in Figure 20, were as follows:

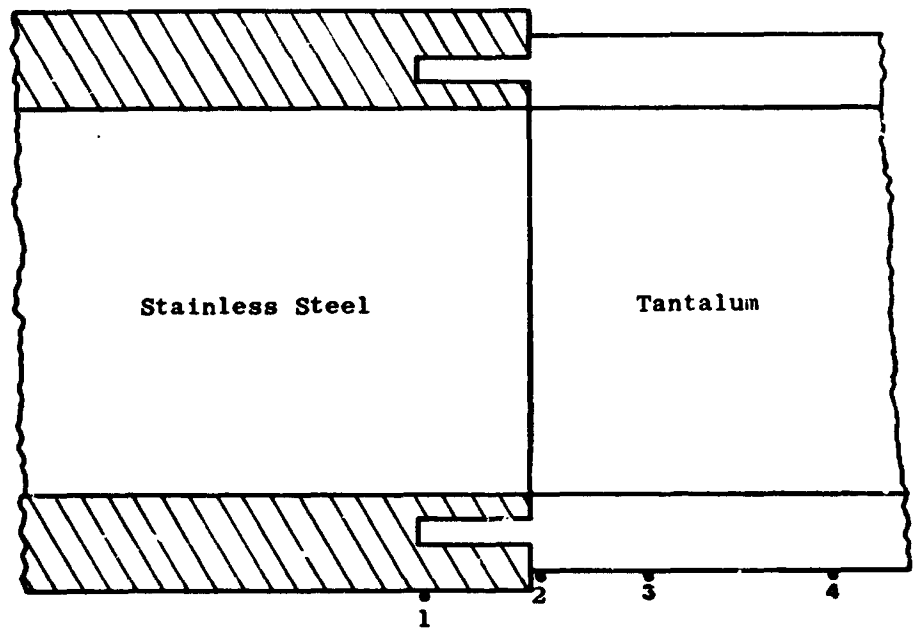
Position #1 - On the stainless steel member at a point equal to the bottom of the groove.

Position #2 - On the tantalum member immediately above the top of the tongue-in-groove area.

Position #3 - On the tantalum member, 0.25 inch above the top of the tongue-in-groove area (slightly above the braze preplacement zone in tubular assemblies).

Position #4 - On the tantalum member, 1 inch above the top of the tongue-in-groove area.

Transient temperatures were measured with a fast response millivolt recorder, shown in Figure 6. Initial testing was conducted with no braze present in the joint area. The purpose of those tests was to explore the previously indicated parameters, to establish those radiation-heat rejection conditions which would tend to produce a greater cooling rate at position #1 (bottom of the groove) than at position #2 (top of the groove), assuming



4 Thermocouples attached to OD of Joint at:
1 bottom of tongue and groove on SS
2 top of tongue and groove on tantalum
3 1/4" from top of tongue and groove on tantalum
4 1" from top of tongue and groove on tantalum

Figure 20. Thermocouple Positions for Directional Solidification Testing

uniform steady state temperatures at those locations prior to the cooling cycle. Determination of the relationship of the transient temperatures at position #3 and #4 versus those at positions #1 and #2 for a given test setup was necessary in these first tests because a thermocouple could not be attached at position #2 when the actual braze alloy was preplaced at the joint.

Preliminary test results (no braze present) established that the tantalum component temperature measurements at position #3 were equivalent to those measured at position #2, under both steady state and transient conditions regardless of the presence or absence of thermal insulation. Temperatures at position #4 varied from those at the other tantalum member temperature readout locations, dependent on the extent and location of thermal shielding employed to achieve a desired test condition. Therefore, measurements at position #3 were used to define the steady state temperatures and cooling rates of the tantalum component for all subsequent thermal cycles used to determine those conditions most conducive toward achieving directional braze solidification in the tantalum/stainless steel assemblies.

The results of the directional solidification testing are presented in Table III. The initial tests, performed without braze alloy present in the joint area, indicated that a slower cooling rate of the tantalum member, relative to that of the stainless steel, could be attained by shielding the outside of the tantalum component and the tongue-in-groove area. The maximum difference in rates was 20°F (11°C)/minute; Ta rate = 140°F (78°C)/minute, SS rate = 160°F (89°C)/minute. The shielding used to produce those relative rates consisted of three concentric, cylindrical layers of tantalum; each layer was separated by 0.010-inch-diameter coiled tantalum wires. Although a reduction in the relative tantalum cooling rate could be achieved, the steady state temperatures across the joint were not equal. The stainless steel temperature, prior to cooling, exceeded that of the tantalum component by 35°F (20°C) (steady state temperatures - SS = 2195°F (1202°C), Ta = 2160°F (1182°C)). Reductions in the number of shields present lessened the temperature difference at a nominal 2160°F (1182°C), but also resulted in greater tantalum cooling rates. These initial results were very encouraging because having braze alloy present

TABLE III

RESULTS OF THERMAL TESTING TO EXPLORE POSSIBLE DIRECTIONAL SOLIDIFICATION IN TA/TYPE 316 STAINLESS STEEL TUBULAR (2-INCH OD) TONGUE-IN-GROOVE JOINTS

Test Number	Thermal Shielding/[(1)] Joint Position	Steady State Temperature[(2)] Before Cooling - °F			Average Cooling Rate[(2)] °F/minute			
		Tantalum	Stainless Steel	Difference	Nominal	Tantalum	Stainless Steel	Difference
	Without Braze Alloy in Area							
1	A	2170	2180	- 10	Maximum	220	185	- 35
2	B	2160	2195	- 35	(a) Maximum	140	160	+ 20
					(b) 75	68	75	+ 7
					(c) 25	23	25	+ 2
	With Braze Alloy in Joint Area							
1	A	2160	2165	- 5	(a) Maximum	210	195	- 15
					(b) 25	26	25	- 1
2	C	2160	2180	- 20	(a) Maximum	178	187	+ 9
					(b) 25	24	25	+ 1
3	B	2160	2195	- 35	(a) Maximum		See Note (3)	
					(b) 25	25	26	+ 1
4	D	2160	2178	- 18	Maximum	138	166	+ 28
5	E	2160	2179	- 19	Maximum	210	174	- 36
6	F	2160	2169	- 9	Maximum	155	157	+ 2
7	G	2160	2160	--	Maximum	138	137	- 1
8	H	2160	2160	--	(a) Maximum	120	136	+ 16
					(b) 25	22	25	+ 3

(1) A - Joint resting on bottom of furnace on tungsten hearth plate; no shields around joint; ten split disc tantalum shields positioned at top of furnace hot zone.
B - Same as A + 3 tantalum shields surrounding outside of tantalum and joint area.
C - Same as A + 1 tantalum shield surrounding outside of tantalum and joint area.
D - Same as A + 3 tantalum shields surrounding outside of tantalum above joint area.
E - Same as A + heat retaining tantalum mass positioned inside of tantalum above joint area.
F - Joint raised 7/8 inch from hearth plate + 3 tantalum shields surrounding outside of tantalum above joint area.
G - Same as F + 4 additional shields on top of tantalum.
H - Same as A + 3 tantalum shields surrounding tantalum above joint area and 4 additional shields on top of tantalum.

(2) Tantalum temperatures were those determined at a position 0.25 inch above tongue-in-groove joint; stainless steel temperatures were those determined at a position equal to the bottom of the groove.

(3) At the maximum cooling rate, the stainless steel temperature did not decrease to less than that of the tantalum component before 2000°F had been reached.

in the joint area was expected to equilibrate steady state temperatures while the heat shielding present would maintain a reduced tantalum cooling rate relative to the stainless steel.

Continuation of the directional solidification testing was performed with J-8400 braze alloy applied to the tongue-in-groove assembly. Thermocouples were attached appropriately and the assembly placed in the vacuum furnace chamber in the desired location, after thermal shielding had been positioned around the assembly. The assembly was then heated to a nominal brazing temperature of 2160°F (1182°C) and the temperatures of the stainless steel and tantalum components determined. The cooling rates of both components were measured, as before, during cooling of the assembly to the solidification temperature of the J-8400 braze alloy (approximately 2000°F (1093°C)). Different nominal rates of cooling were employed to determine whether that variable had a significant effect on the differences in the components temperatures at any given time. All of the previously indicated factors, which influenced the relative heat rejection tendencies of the assembly components, were studied to establish those conditions which resulted in (1) a uniform steady state temperature distribution across the tongue-in-groove joint area, and (2) a lower tantalum cooling rate in relation to that of the stainless steel. The data from the testing, with braze present in the joint, indicated that the above requirements were met when the following experimental conditions were employed:

1. The assembly, stainless steel end down, was resting on the bottom of the furnace atop a tungsten hearth plate.
2. Three cylindrical, concentric tantalum shields (tantalum shield material 0.003 inch thick) were positioned around the tantalum component. The shield package extended from the top of that member to the top of the tongue-in-groove joint area.
3. Four disc tantalum shields were placed on top of the tantalum component.
4. Ten split disc Ta shields were located at the top of the furnace hot zone.

No significant effects on directional braze solidification were observed when the nominal rate of cooling from the brazing temperature was varied from 25°F (14°C)/minute to a maximum value of approximately 140°F (78°C)/minute; i.e., the measured intercomponent temperature differential was constant for any given stainless steel component temperature, regardless of the cooling rate employed, during cooling to 2000°F (1093°C) which approximates the solidus temperature of the J-8400 braze alloy. For example, when a maximum furnace cooling rate was used, the stainless steel component cooling rate of 136°F (76°C)/minute exceeded that of the tantalum member by 16°F (9°C)/minute. Thus, after cooling for one minute, the stainless steel temperature was measured as 2024°F (1107°C) and the tantalum temperature was 2040°F (1115°C). The same stainless steel temperature and temperature differential were observed approximately 5.4 minutes after the start of cooling at a nominal rate of 25°F (14°C)/minute, indicating that either a slow or rapid rate produced the same transient temperature differentials in the joint components, at least to the point where freezing of the braze alloy occurred.

Two tubular, tantalum/Type 316 stainless steel joints (S/N 12 and S/N 14) were vacuum brazed under the conditions described above which appeared most probable for achieving directional braze solidification in those tongue-in-groove assemblies. S/N 12 was cooled at a basic furnace rate of 150°F (84°C)/minute, and S/N 14 at a rate of 25°F (14°C)/minute, from the 2160°F (1182°C) brazing temperature to approximately 1400°F (760°C). Both joints were ultrasonically inspected to determine the possible beneficial effects of such thermal processing. Reiterating, the basic premise for studying the directional solidification process variation was that controlling the freezing pattern of the J-8400 braze alloy could reduce the extent of microshrinkage void formation. The ultrasonic inspection revealed that the assembly cooled at the fastest rate contained the least microshrinkage. Since that higher nominal rate generated greater top to bottom transient temperature differentials in the joint area, the nondestructive inspection data, to some extent, pointed out that the directional solidification technique for brazing bimetallic joints could be potentially advantageous. However, a comparison of the ultrasonic results (for both of the directionally solidified joints) with previous inspection date for the initial tubular production joints brazed at 2160°F

(1182°C) and slow cooled (25°F (14°C)/minute) with no shielding directly in contact with the joint components, indicated that the previous method produced better assemblies in some instances. Based on that comparison, it appeared that the slow cool-homogenization approach was a better method for minimizing braze microshrinkage. It was fully realized, however that more definitive testing would be required to completely evaluate the directional solidification concept. Since the equipment and instrumentation requirements for further exploration of the directional concept were quite complex, and further evaluation beyond the scope of the present program, directional solidification studies were discontinued.

Radial Temperature Distribution Experiments

Following the directional solidification studies, it was decided to try an alternative approach to improve the braze quality. Some of the initial tubular brazed joints, particularly (S/N 5 and S/N 7), exhibited a greater degree of microshrinkage, primarily in the inner braze annuli, than others. Several factors, to be discussed further in later paragraphs, may have contributed to this behavior. One of those factors was nonuniform temperature distribution across the wall of the assemblies during brazing, which could have effectively caused solidification of the braze alloy to occur at some preferential locations, and potentially have isolated a given braze area from the main supply fillet, while freezing was in progress. Another way in which a nonuniform temperature distribution could have contributed to more inner braze microshrinkage was that braze solidification could have occurred from the outside toward the inside of the joint. Reduction of this tendency by reversing the freezing direction (ID to OD) was desirable since the inner braze area is the more important from a structural standpoint. It was decided this reversed solidification direction could be realized by reversing the apparent temperature distribution; i.e., outside joint temperatures should be somewhat higher than inside temperatures. Thus, experimentation was undertaken to determine the thermal shielding conditions which would produce higher relative temperatures on the outside of the tubular assemblies and thereby induce braze solidification to take place from the inside toward the outside of the joints.

Thermal Equilibrium Experiments

The general method employed to establish optimum radiant shielding conditions for the brazing of a tantalum/Type 316 stainless steel, tongue-in-groove assembly is contained in the following paragraph.

The thermal shielding used at the top of the furnace hot zone consisted of either 1, 4, or 10 layers of tantalum discs, each 0.005 inch thick. Some of the discs for an individual shield package were diametrically split, while others contained only 0.5-inch-diameter holes for thermocouple penetration into the furnace hot zone. The thermal shielding in the vicinity of the assembly being brazed, consisted of (1) two concentric, cylindrical tantalum shields, each 6 inches long, covering the entire length of the joint, placed between the furnace heating elements and the tubular joints, and/or (2) four continuous tantalum disc shields resting on top of the tantalum component of the assembly. The joint was placed in the vacuum furnace and the heat shielding arranged around it.

The assembly was heated to the desired brazing temperature and steady state temperatures were measured at selected ID and OD joint locations. The assembly was cooled at 25°F (14°C)/minute to 1400°F (760°C); thereafter, it was cooled to room temperature at nominal furnace rate. The thermocouple measuring positions, schematically shown in Figure 21, for the test cycles are listed below:

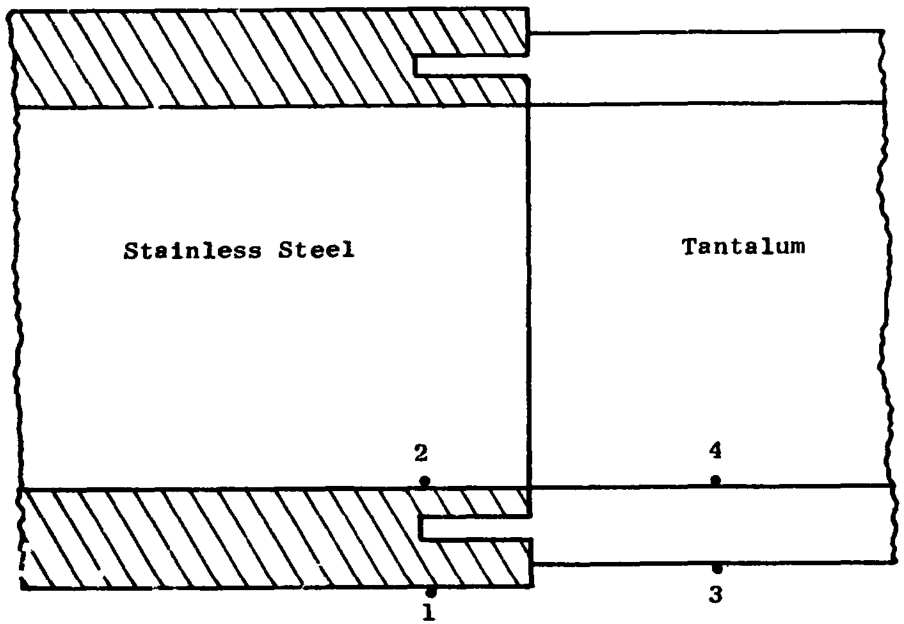
Position #1 - On the stainless steel OD at a point equal to the base of the groove.

Position #2 - On the stainless steel ID at a point equal to the base of the groove.

Position #3 - On the tantalum OD above the braze area (0.5 inch above the top of the groove).

Position #4 - On the tantalum ID above the braze area (0.5 inch above the top of the groove).

A ten-layer split disc furnace top insulation package, and no direct part shielding, were employed for the brazing of joints S/N 1 through S/N 10 and S/N 15. The steady state temperature measurements



4 Thermocouples Attached to OD and ID of Joint at:

1 bottom of tongue and groove on the OD of the SS

2 bottom of tongue and groove on the ID of the SS

3 1/2" from the top of tongue and groove on the OD of the tantalum

4 1/2" from the top of tongue and groove on the ID of the tantalum

Figure 21. Thermocouple Positions for Thermal Equilibrium Testing

at positions No. 1 and No. 2, during brazing of those assemblies, indicated slightly higher temperatures at the outside surfaces than at the inside (ΔT = 10°F (5.5°C). These temperature conditions were expected since the furnace heating element surrounded the assembly. However, on cooling at a rate of 25°F (14°C)/minute from the brazing temperature, inversion of those conditions was observed shortly before the liquidus temperature (~ 2050°F (1121°C))of the J-8400 braze alloy had been reached; i.e., the inside joint temperature, during braze solidification, exceeded that at the outside. This phenomenon most probably resulted in the undesired outside-to-inside freezing of the braze alloy.

The first attempt to correct the described condition involved the placement of two cylindrical shields around an entire assembly to reduce heat rejection from the outside surfaces. Results of this initial modification generated the desired temperature gradient conditions, but the effect was too pronounced. Thus, the steady state temperature of the tantalum component at position No. 4 was 72°F (40°C) less than that of the stainless steel member at position No. 1. The second modification, i.e., four continuous disc shields positioned on top of the tantalum, in addition to the previous two cylindrical shields around the joint, reduced the gradient to 52°F (29°C). Thereafter, the furnace top shielding package was changed from the split disc type to the continuous disc configuration. Subsequent brazing trials, conducted with a four-continuous-disc furnace top shield stackup, indicated small OD-ID transicent and steady state temperature gradients (~ 20°F (11°C)), with the inside surface being cooler. This was the desired thermal distribution condition, and the indicated shielding parameters were selected for use in the preparation of subsequent production joints.

In summary, the ultrasonic inspection of several tubular tantalum/ Type 316 stainless steel brazed assemblies revealed that the slow cool-homogenization approach produced generally superior braze freezing characteristics in the tongue-in-groove area than those exhibited in "directionally solidified" assemblies. Modifications of the thermal insulation setup were necessary, however, to establish those conditions which would result in the initial braze solidification at the inner braze annulus of the tubular joints. After several trials, a shielding technique was selected for the brazing of subsequent production joints.

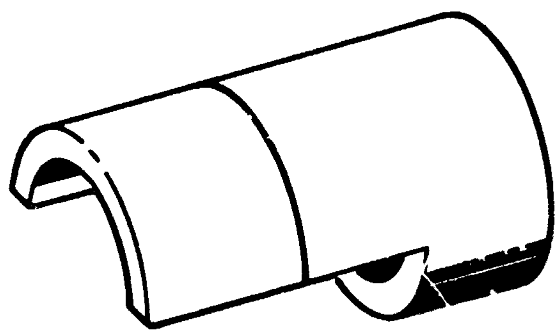
DEVELOPMENT OF ULTRASONIC METHOD FOR INSPECTING TUBULAR ASSEMBLIES

The primary purpose of this portion of the investigation was to develop a reliable ultrasonic technique for the nondestructive inspection of the brazed tantalum/Type 316 stainless steel transition joints. The annular braze areas at the inside and outside of the tongue member represented the most important sections of the joints from a structural standpoint, and control of the braze quality therein was vital to realize optimum joint characteristics. Thus, the function of the ultrasonic inspection was to accurately depict the braze characteristics in those areas, and thereby establish the integrity and soundness of the fabricated brazements. The two essentially separated braze sections or bands posed a difficult inspection problem, even for ultrasonics with its inherent capability for exploring the internal volume of a component or assembly. The layers are relatively close to each other and to the tubing surfaces (refer to Figure 2), and the ability to ultrasonically resolve each portion of the five layer sandwich (stainless steel-braze-tantalum-braze-stainless steel) was, therefore, difficult. The situation was compounded because increased power levels were required to permit inspection of the inner braze annuli at the same detection sensitivity as that related to the outer braze areas. Greater power inputs were necessary because the sonic beam had to pass through the somewhat inhomogeneous outer braze material to reach the inner zone. The described difficulties in the ultrasonic inspection of the transition joints were eliminated by the use of suitable inspection standards so that relative inspection sensitivities at the two braze layers could be evaluated and adjusted. Preparation of such standards required the machining of well defined, artificial defects into the brazed areas of a representative tubular tongue in groove assembly. These artificial defects were of various sizes so that different levels of inspection sensitivity could be realized in subsequent examinations. Other assemblies were brazed, ultrasonically inspected, and subsequently examined metallographically, to verify the capability of the developed ultrasonic method for indicating the condition of a particular brazed joint. The preparation and evaluation of standards, metallographic-ultrasonic data correlation to verify inspection capabilities, and the ultrasonic techniques employed are discussed in following paragraphs.

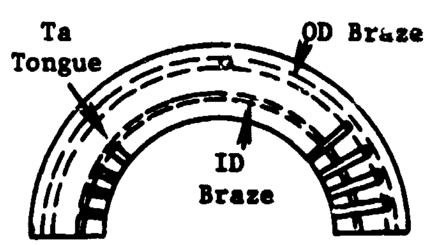
Ultrasonic Standards Preparation and Evaluation

The equipment and general ultrasonic technique employed for tubular joint inspection was the same as that used in inspection of sheet brazed assemblies, with some minor modifications. Both "C-scan" and "modified A-scan (X-Y)" recordings were obtained for all tube joints in this phase of the investigation. The first tubular assembly brazed was intended for use as an ultrasonic calibration standard. The joint was vacuum brazed at 2160°F (1182°C)/5 minutes and cooled at 25°F (14°C)/ minute from the brazing temperature to 1400°F (760°C). Thereafter, it was ultrasonically inspected to insure that the areas selected for subsequent hole placement were essentially defect free, and any porosity present in the solidified braze would be negligible in comparison with the holes to be machined. The joint was cut so that the calibration holes could be machined directly into each of the braze zones from the ID of the joint, as shown in Figure 22. During the machining process the wide-gap outside braze cracked around most of the circumference. This ultrasonically obscured all the holes in the inner braze annulus and most of those in the outer braze zone. Thus, it became necessary to use a second tubular joint for the calibration standard. The machining technique for this assembly was altered to eliminate the braze cracking problem; i.e., the joint was not sectioned through the brazed area to simplify the hole machining operation. The radial, flat-bottomed, holes in the tube joint were produced by electrical discharge machining (EDM) with a special electrode designed to reach the desired interior positions. The smallest hole that could be prepared by that processing technique had a diameter of 0.007 inch. The radial holes machined into both braze areas were, therefore, 0.050, 0.020, 0.010 and 0.007 inch diameter. The desired axial hole in the outer braze annulus could not be produced, since the joint area was not exposed by transverse sectioning.

Experiments with tantalum and stainless steel sheet materials were conducted to determine the best method for preventing braze flow in selected areas, for subsequent fabrication of an intentionally misbrazed, tongue-in-groove, tubular assembly. Those experiments indicated that mechanical removal by filing and subsequent careful painting of braze "stop-off" materials on specific areas could be successfully used.



Overall View of the Calibration Standard



Transverse View of the Standard Depicting Hole Locations

Figure 22. Sketch of Ta/Type 316 SS Tubular, Tongue-in-Groove Brazed Joint Used as Ultrasonic Calibration Standard.

Thereafter, the outside diameter of the tongue of a tantalum joint component was filed to remove 0.005 inch of material over two separated 90° portions of the tongue circumference. Those two areas and alternate 90° sectors on the ID were then painted with "stop-off". The joint components were then assembled and braze alloy preplaced at both the joint OD and ID in the areas where no "stop-off" was present. The assembly was then vacuum brazed at 2160°F (1182°C) for 5 minutes, and cooled at 25°F (14°C)/minute to 1400°F (760°C). Visual examination of the joint after brazing indicated that the desired braze flow characteristics were obtained, as schematically shown in Figure 23. Ultrasonic inspection of that joint, before metallographic examination, also indicated that the desired results had been achieved; i.e., adjacent 90° sections on the inside and outside of the tongue and groove were either completely filled with braze or contained none at all. The intentionally misbrazed tubular joint was examined metallographically at two transverse planes through the tongue and groove joint area. Those examinations verified that the ultrasonically predicted braze-no braze conditions in the assembly had been achieved. The excellent agreement between the destructive and nondestructive data pointed out the capability of the ultrasonic technique for determining completely nonbonded areas in the brazed joints.

Ultrasonic Inspection Sensitivities

Reflected signals from the ultrasonic scanning of the flat-bottomed holes in the ultrasonic standard tube assembly were compared with those obtained from the natural defect present in one of the overlap brazed joints. It was determined that ultrasonic sensitivities used in the sheet sample inspection would also be adequate for inspection of tubular brazed joints. Thus, it was no longer necessary to use the natural calibration defect in the overlap specimen to assist in further ultrasonic inspection of tube joints.

Ultrasonic "C-scan" recordings at various sensitivities were made on several of the initially prepared tubular assemblies to select the most meaningful sensitivity settings and techniques for following tubular assemblies inspection. However, only one sensitivity setting was

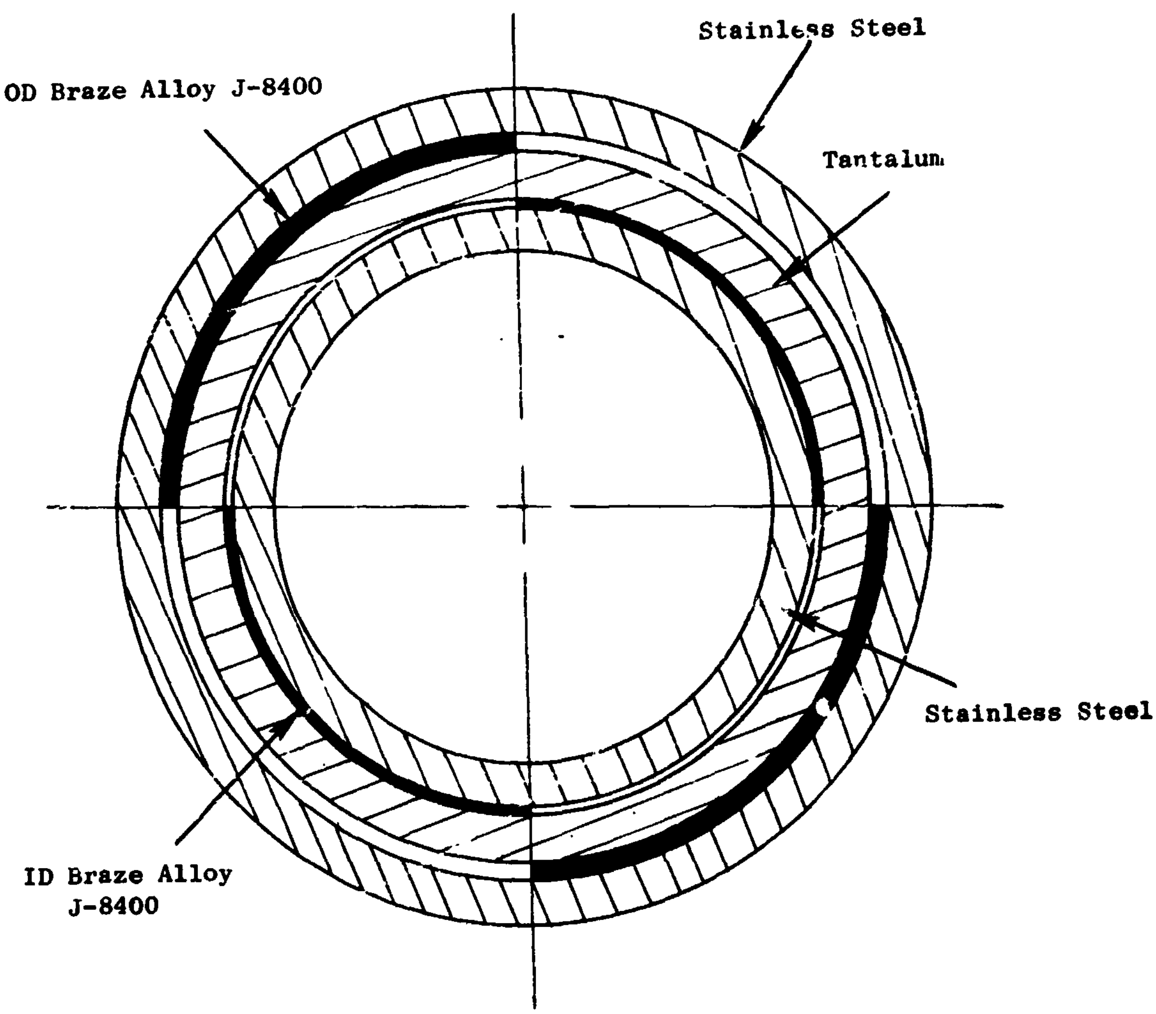


Figure 23. Sketch of Transverse Section of Intentionally Misbrazed Ta/Type 316 SS Tubular, Tongue-in-Groove Joint Showing Areas of Brazing. Assembly Used as Ultrasonic Standard.

utilized in generating the X-Y recordings. This sensitivity was adjusted such that a 0.010-inch diameter calibration hole in the braze annuli was represented on the X-Y recording as a 10 unit amplitude signal and a 50 percent of full scale amplitude on the ultrasonic display unit. Figure 24 represents a typical "modified A-scan" recording obtained from the inspection of a tubular tantalum/Type 316 stainless steel brazed joint. Specific planes in some tubular joints were selected for the metallographic correlation efforts because the X-Y recordings of those planes demonstrated a variety of signal amplitudes. The selected planes also contained well defined transitions from one ultrasonically indicated condition to another, which permitted the determination of the correlation between signal position and actual physical location on the assembly being examined.

CORRELATION STUDIES

The purpose of the correlation study was to determine by metallographic examination of tubular joints, the nature of defects producing various ultrasonic indication amplitudes and configurations and, based on these results, to establish a criteria for acceptance or rejection of the joints by ultrasonic inspection only. Ultrasonic inspection of a component or assembly depends on the penetration and propagation of a low-magnitude, mechanical energy sonic beam through the material being examined. Structural variations or defects within a material that significantly influence stress distribution under an applied mechanical load, would have a corresponding effect on the transmission and distribution of a sonic wave passing through the area of significance. Defects with sharp corners or large length-to-thickness ratios represent high-stress concentration areas which tend to reduce the strength of a material to a greater extent than a similar size defect having a spherical configuration. Transmission of an ultrasonic beam through a zone containing defects is similarly affected more by the degree of stress concentration than by the physical size of the flaws, providing the size of the latter does not approach objectionable limits. Thus, metallurgical interactions, drastic chemistry variations and round voids tend to produce relatively slight disturbances in the ultrasonic beam transmission in comparison to those induced by

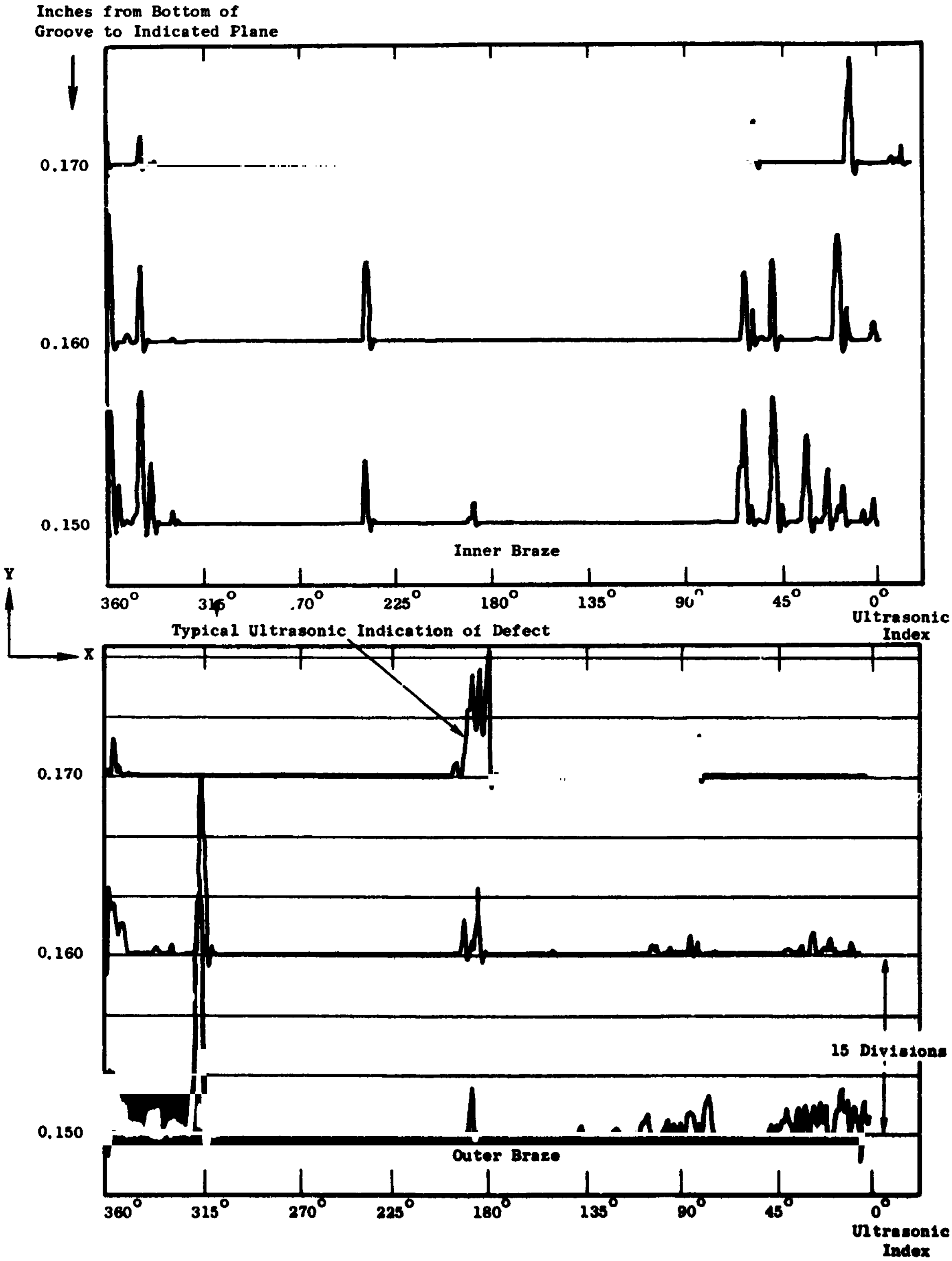


Figure 24. Typical Ultrasonic "Modified A Scan" Presentations Obtained from Inspection of Transverse Planes Through the Tongue In-Groove Brazed Area of Correlation Study Joint S/N 12.

cracks, platelike voids, and other high-stress concentrating defects. These factors were considered in the inspection of the tubular joints.

The ultrasonic velocity change in tantalum was beneficial in the preparation of well-defined, "C-scan" (plan view) recordings of the joint areas because the back surface (ID surface of tube joint) indication shifted to a later time where tantalum was encountered. That is, the propagation velocity of the ultrasonic beam in tantalum is much less than in the stainless or braze alloy and, therefore, appears as an apparent "increase in thickness." Thus, the "C-scan" recordings showed a sharp demarcation line (white to black) when the bottom of the groove was reached. This shift was also used in determining the physical location of the "modified A-scan" recordings and especially in determining the reference position for comparison of ultrasonic recordings with metallographic sections. Also, the degree of uncertainty in the location of the source of an ultrasonic indication was reduced through minimizing possible refraction by inspecting the tubular joints in the radial direction only.

Two joints (S/N 6 and 7), intended for the correlation investigation, were vacuum brazed at 2160°F (1182°C)/5 minutes, using initially selected shielding conditions, and subsequently cooled, during braze solidification, at a rate of 25°F (14°C)/minute. These assemblies were ultrasonically inspected and areas within the joint selected for microstructural examination. Thereafter, they were cut perpendicular to the assembly axis, adjacent to the tongue-in-groove area, in preparation for metallography. The assemblies were then rough machined by surface grinding to approach the desired transverse planes to be examined. The direction of approach into the joint area was from the stainless steel end of the assembly. The first of these correlation study joints was examined metallographically near the preselected transverse inspection plane. The examination revealed cracks present in the solidified braze alloy in a 90° section of the inner annulus between the tantalum tongue and stainless steel groove. The observed cracking was believed to have resulted from the preparatory surface grinding operation, since the earlier ultrasonic inspection had not indicated the presence of any such gross defect. The joint had been prepared for metallographic examination by removing material from the stainless steel end of the assembly to accurately determine the groove base location which was the measured reference point for ultrasonic inspection. It was postulated that when the actual joint area was reached, the support of the braze material, provided by the interconnected stainless steel material below the groove, was removed leading to the observed braze failure. The metallographic processing of both correlation study specimens was interrupted in order to reinspect the joint areas by ultrasonics to verify that the observed cracking had been induced by the preparatory machining operation. The ultrasonic reinspection demonstrated that the failures had indeed been caused by the metallographic processing; and replacement joints were, therefore, selected to complete the study.

Ultrasonic inspection of the "directional solidification" tubular study joints (joints S/N 12 and 14) indicated that their quality was below acceptable production joint standards. However, the ultrasonic X-Y recordings for those joints displayed several interesting features, and they were, therefore, chosen as the replacement joints. A third assembly (joint S/N 5) was also selected for the correlation investigation. Joints S/N 5 and S/N 12 were selected for transverse planes examination and joint S/N 14 for longitudinal planes study. Specific planes in each joint were selected for metallographic examination, based on the ultrasonic inspection data pertaining to those assemblies.

Resolution of the braze cracking problem, during metallographic preparation of joints S/N 5 and 12 for transverse sections, was accomplished by observing two additional precautionary measures during the initial material removal stages. The first was to leave the interconnected stainless steel material intact by approaching the brazed area from the tantalum end of the joint. This new technique required more lapping than the previous procedure, because the initial transverse cut, through the tantalum member, had to be made above the external braze fillet area. The second precautionary measure observed was the bulk material removal by circular lapping only. A combination process of back-and-forth grinding coupled with lapping had been utilized previously. The circular lapping substantially reduced the extent of stresses induced in a direction perpendicular to the minimum supported braze area. The transverse planes examination, after completion of the metallographic processing, revealed that the problem had been resolved.

Preparation of joint S/N 14, for the microstructural examination of longitudinal planes, presented a somewhat different, but related, problem; i.e., residual stresses present in the tongue and groove area after brazing. Stress imbalance can produce catastrophic failures of the solidified J-8400 braze alloy during longitudinal sectioning unless precautionary measures are observed. To overcome this difficulty, the entire assembly was encased in thermal setting plastic before axial sectioning to inspect a particular angular position. The mounting material thus provided the required support in the braze area and prevented failure during sectioning.

The correlation study joints were processed to determine the microstructures present at the following locations in the brazed areas:

Joint S/N 5 - At two transverse planes through the joint area, 0.180 inch and 0.120 inch (axial distances) from the bottom of the groove in the stainless steel component.

Joint S/N 12- At two transverse planes through the joint area, 0.160 inch and 0.110 inch (axial distances) from the bottom of the groove in the stainless steel component.

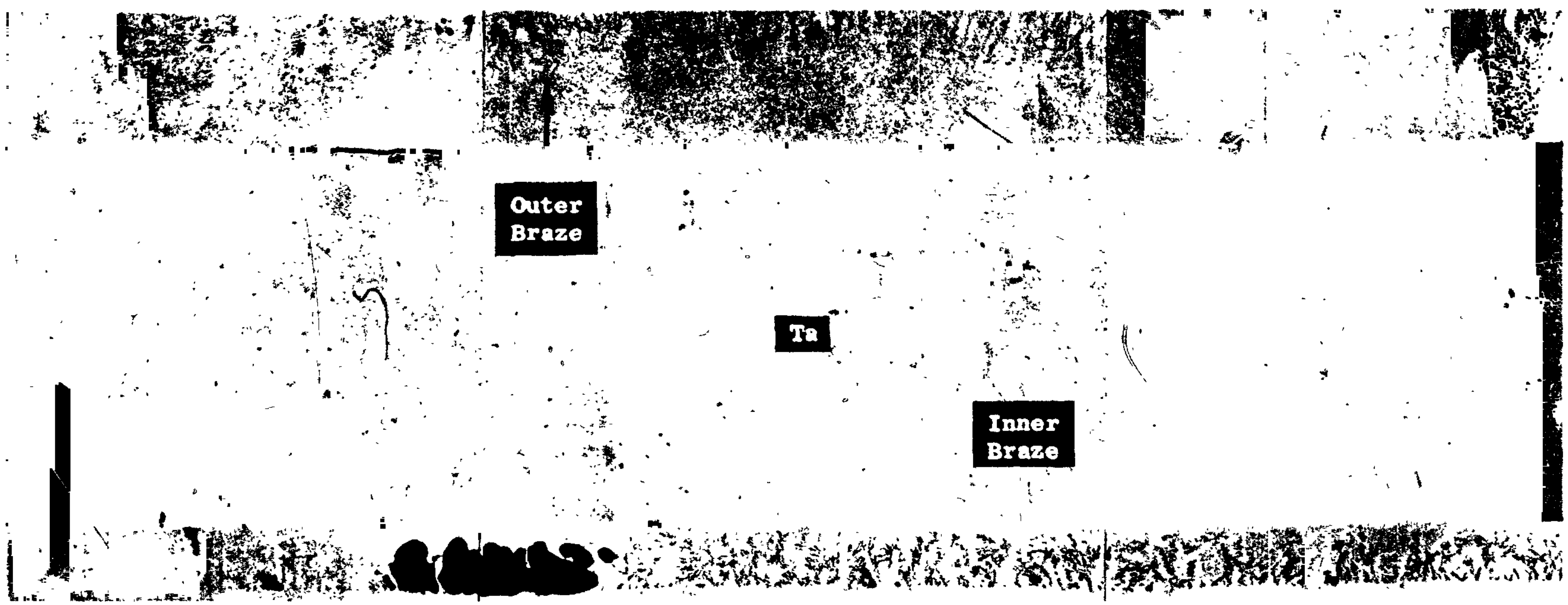
Joint S/N 14- At two longitudinal planes, 104° and 180° counterclockwise, rotational distance from an arbitrary ultrasonic reference point.

The microstructures at each plane were compared on a point-by-point basis with the "modified A-scan" presentations for those planes to establish the degree of correlation, and thereby determine the capability of the ultrasonic technique for representing the quality of the joints.

Photographs (45X) along the tongue-in-groove brazed areas were obtained for each plane of examination in the correlation samples. These photomicrographs were then compared directly with the respective "modified A-scan" (X-Y) recordings for the different planes. Figure 24 presents a typical A-scan recording for several planes in joint S/N 12;

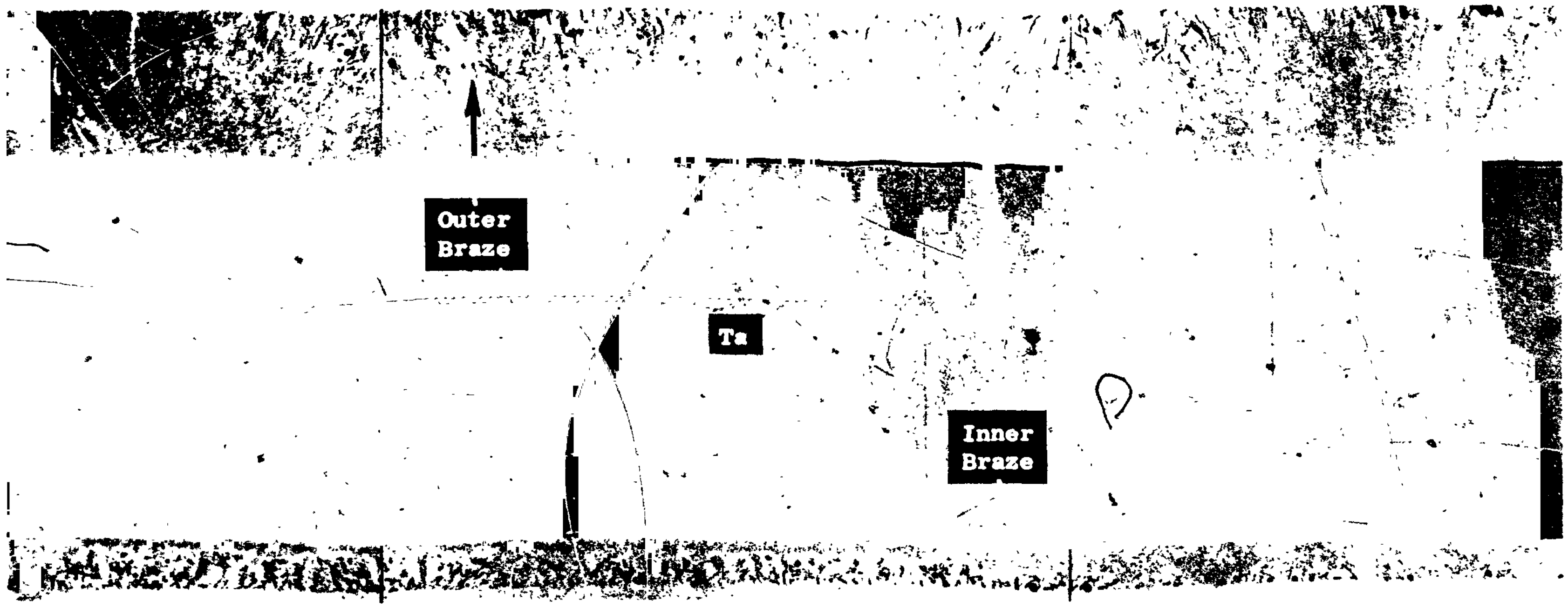
Figures 25, 26 and 27 depict the unetched photomicrographs obtained at different angular positions around the transverse planes of examination in those assemblies. The comparisons revealed the generally good correlation between the ultrasonic data and the actual microstructures present. The majority of ultrasonic indications of defects were produced by the presence of microshrinkage voids in the solidified J-8400 braze alloy. Wherever the ultrasonic recordings showed no vertical signal displacement, no significant defects were observed. Conversely, recording deflections of a significant magnitude were directly related to the size of the defects; i.e., the greater the recording signal height, the larger the effective size of the corresponding defect. The defects found tended to be smaller in circumferential dimension than was predicted by comparison of the respective defect signal with the calibration standard; i.e., a defect, which produced an indication equivalent to that obtained from a 0.010-inch-diameter calibration hole, tended actually to be less than 0.010 inch in circumferential dimension.

The metallographic examination of the transverse planes in joints S/N 5 and S/N 12 revealed that the tongue and groove diameters were not concentric and the braze thicknesses correspondingly varied from the anticipated values. The inner braze thicknesses thus ranged from $\sim$ 0.0005 inch to 0.008 inch; the outer braze annular dimensions were also observed to correspondingly vary. This behavior tended to change the nature of any defects present in the braze areas, primarily in the inner braze annuli. At the closest diametric point of approach, the restricted volume caused voids present to have very thin platelike configurations, and they, therefore, represented stress concentrations equivalent to that of a natural crack. This type of effect was observed in joint S/N 5; a large, almost continuous, indication of defect was found on a number of the "A-scan" planar presentations of the inner braze area of that assembly. The area in question had an axial length of about 0.1 inch and covered approximately 180° of the joint circumference. Extensive microstructural examination (1000X) revealed that a large portion of the signal was produced by the presence of microscopic voids at the tantalum-braze interface. Further, one small area, approximately 10 degrees in circumferential length, actually exhibited the presence of



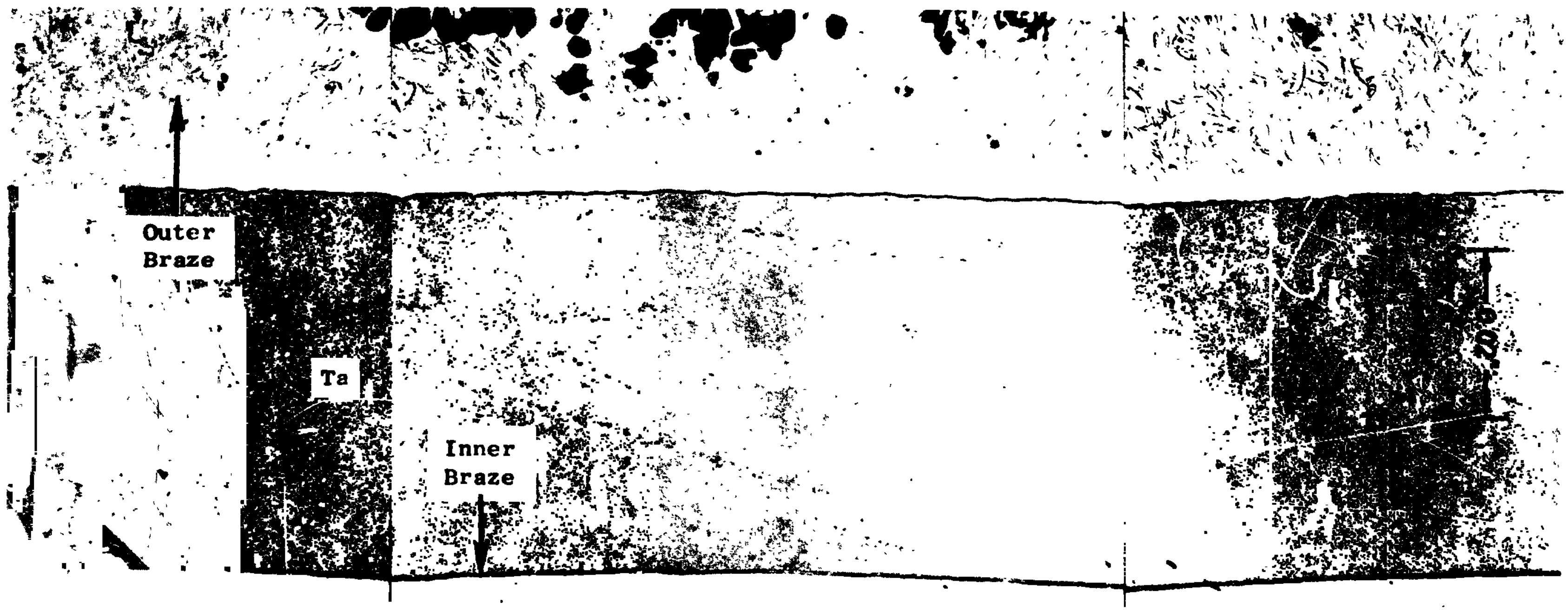
45X
Unetched

Figure 25. Unetched Photomicrographs from Correlation Study Joint S/N 12 at 0.160-Inch Transverse Plane of Inspection. Circumferential Position 245° Rotation from Arbitrary Index. (Refer to Figure 24.) Note Inner Braze Defect.
(Left - G54011X, Middle - G54011Y, Right - G54011Z)



45X
Unetched

Figure 26. Unetched Photomicrographs from Correlation Study Joint S/N 12 at 0.160-Inch Transverse Plane of Inspection. Circumferential Position 270° Rotation from Arbitrary Index. (Refer to Figure 24.) Defect-Free Area.
(Left - G54011S, Middle - G54011T, Right - G54011U)



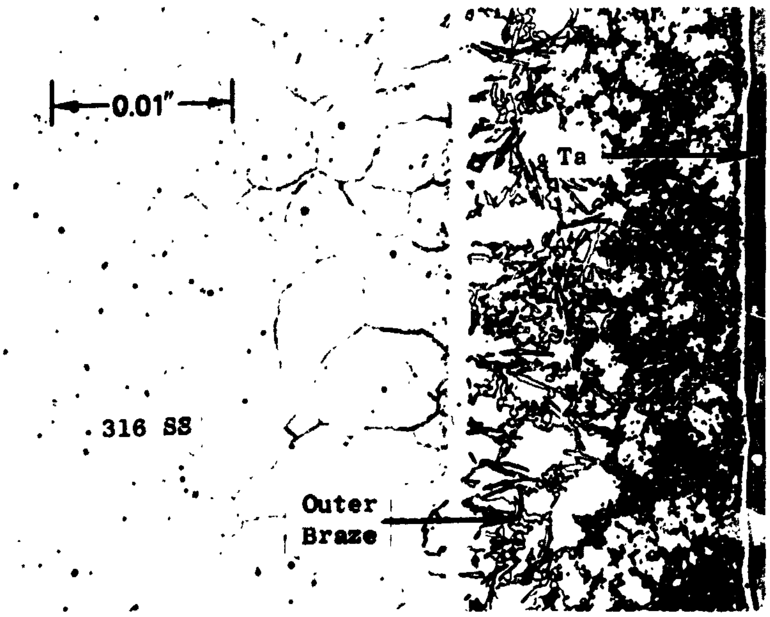
45X
Unetched

Figure 27. Unetched Photomicrographs from Correlation Study Joint S/N 12 at 0.160-Inch Transverse Plane of Inspection. Circumferential Position 315° Rotation from Arbitrary Index. (Refer to Figure 24.) Note Outer Braze Defects. (Left - G54011H, Middle - G54011I, Right - G54011J)

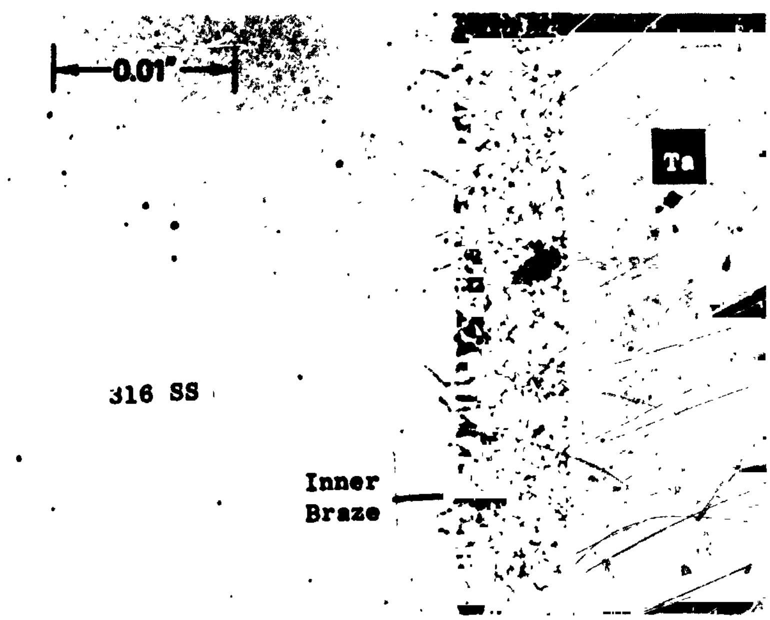
microcracks at that interfacial location. The shape and extent of the ultrasonic signals generated at that location were materially different from any other indications of defect encountered; thus, the future identification of any rejectable assembly would be relatively straightforward. The microstructural examination of the other transverse plane correlation sample (joint S/N 12) also revealed the presence of some microcracks in the thin brazed area. Since the processing, used in metallographic preparation of these brazed assemblies, had been shown to be capable of causing cracking of the braze material, two other transverse planes in joint S/N 5 were very carefully prepared for additional microscopic examination. Those examinations revealed that the metallographic process was still somewhat in question and would require refinement to eliminate the cracking difficulty.

The microstructures present at the longitudinal planes of examination in joint S/N 14 could not be compared completely with the X-Y ultrasonic recordings because those scans had been obtained by essentially transverse sweeping of the joint at separated (0.010 inch) planes. Thus, comparisons could only be made at the points of intersection between the two longitudinal planes and the multiple ultrasonic transverse planes. The microstructural study again provided evidence of the eccentric relationship of the tongue and groove. The study further demonstrated the capability of ultrasonic inspection for the identification of the brazed characteristics of tongue-and-groove tubular assemblies. In fact, almost 100 percent agreement between the ultrasonic data and the physical structures present was realized. The defects encountered were all braze microshrinkage cavities.

The correlation joints were also examined in the etched condition to determine the extent of the metallurgical interactions between the J-8400 braze alloy and the tantalum and stainless steel parent metals, at various positions in the tongue and groove area. Typical microstructures obtained are presented in Figure 28. Microhardness surveys (Knoop - 25 gms load) were also made across each plane of examination to assist in the determination. Figures 29 and 30 depict typical hardness graphs obtained from these measurements on transverse planes in joints S/N 5 and S/N 12. Some observations from the examination and hardness testing of joints S/N 5, 12 and 14 follow:



100X
Etchant: NH_4-HNO_3-H_2O



100X
Etchant: NH_4F-HNO_3-H_2O

Figure 28. Typical Microstructures Present at Inner and Outer Braze Annuli of Correlation Study Joints S/N 5 and S/N 12. [Upper - G750112-1 (S/N 5), Lower - G54015K (S/N 12)]

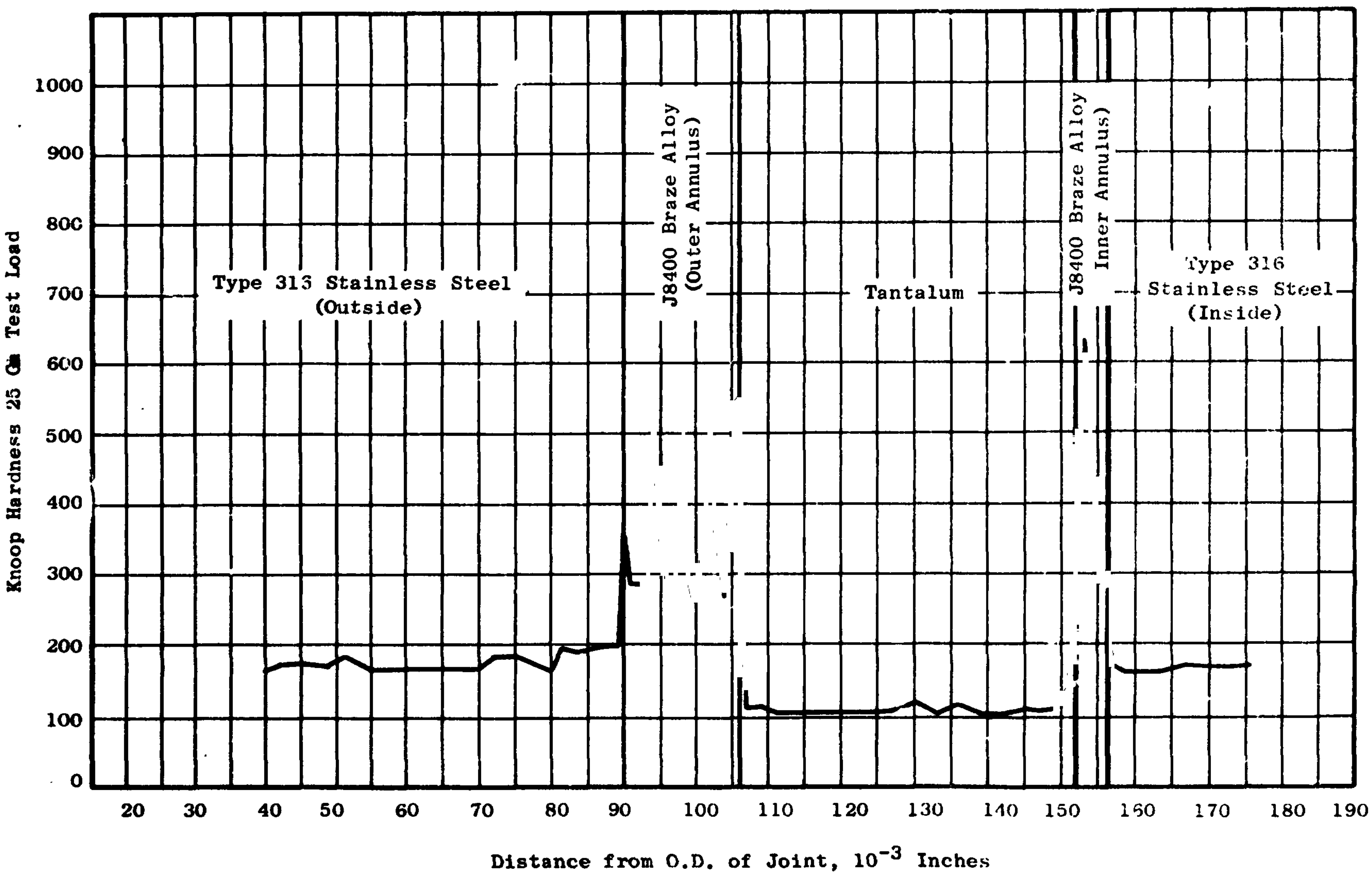


Figure 29. **Hardness Transverse Across the Wall of Ta/Type 316SS Tongue-In-Groove Tubular Brazed Joint S/N 5 at a Transverse Plane Through the Brazed Area, 0.180" from the Bottom of the Groove.**

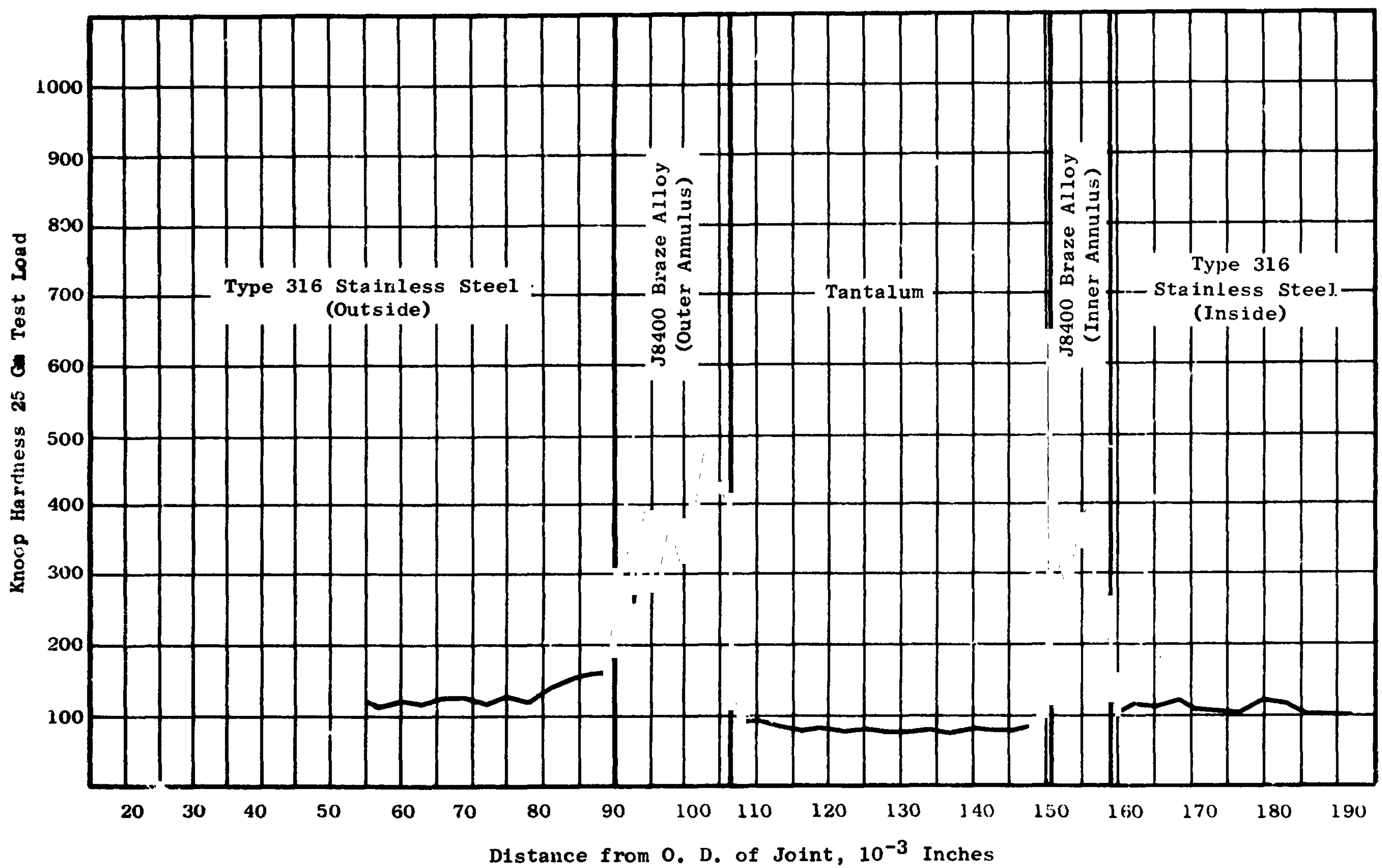


Figure 30. Hardness Transverse Across the Wall of Ta/Type 316SS Tongue-In-Groove Tubular Brazed Joint S/N 5 at a Transverse Plane Through the Brazed Area, 0.160" from the Bottom of the Groove.

1. Metallurgical reactions between the tantalum and stainless steel parent metals and the J-8400 braze alloy, occurring during the brazing operation, resulted in (a) changes in the chemistry of the braze alloy at different positions in the joint area, and (b) greater intergranular braze penetration into the stainless steel at the outer braze annular zone than at the inner zone. These observations were based on the different metallographic etching characteristics of the braze and stainless steel at various locations in the joint. The extent of braze compositional changes in the tubular assemblies was greater than that observed for the brazed overlap specimen prepared under generally the same thermal conditions (see Figure 14). Conversely, the intergranular braze penetration into the stainless steel of the tubular joints was measurably less than that observed in the overlap specimen at a comparative location. These results were attributed primarily to the fact that a lesser quantity of braze per unit area was available for the tongue-in-groove tubular assemblies than for the overlap specimen.

2. An intermetallic phase formed at the tantalum-braze, probably during the initial portion of the braze cycle, which thereafter minimized further braze diffusion reactions with that component.

3. Microshrinkage voids were formed interdendritically next to the stainless steel, implying that braze solidification had started at the tantalum tongue ID and OD surfaces.

4. The braze alloy had a significantly higher hardness than the tantalum and stainless steel base metals. It was not possible to obtain conclusive hardness data on the tantalum-braze intermetallic because of its thinness; however, there were indications that the intermetallic hardness was greater than that of the braze.

5. The hardness data also provided evidence of the braze chemistry variations in the "U" shaped braze cavity, as well as verifying the depths of braze-base metal reaction zones in the tantalum and stainless steel parent metals.

6. The hardness of the parent metals away from the brazed areas was different dependent on the brazing thermal cycles employed. Thus, higher hardnesses were measued in joint S/N 5 than in joints S/N 12 and 14. This behavior was expected since the former joint had been brazed at 2160°F (1182°C) only, whereas, the latter two assemblies had seen two brazing cycles at 2160°F (1182°C) and 2190°F (1199°C).

The results of the metallographic-ultrasonic correlation efforts demonstrated that the described ultrasonic technique had the capability for detecting defects which might prove detrimental to the strength of the brazed assemblies. In fact, the high inspection sensitivities employed made possible the detection of minute or relatively innocuous flaws, such as microvoids (0.0005-inch-diameter) or abrupt compositional changes in the braze materials. These effectively insignificant defects produced amplitude signals on the modified "A" scan recordings ranging from one to ten scale divisions in magnitude, depending on their physical position and relative abundance in the joint areas. The more potentially detrimental structural defects caused ultrasonic signal amplitudes at least 20 scale divisions in size (see Figure 24). Using these correlation results, a criterion was established for the acceptance or rejection of production joints. The criterion was based on ultrasonic inspection performed at the same sensitivity as the correlation studies. Thus, defects causing a deflection greater than 15 scale divisions in magnitude were judged objectionable, and those inducing deflections less than 15 scale divisions were deemed acceptable. As an alternative to this criterion, joints could be accepted or rejected based on an inspection at lower sensitivity. Of course, for this alternative new indication amplitudes for acceptance or rejection would have to be determined. Regardless of which approach is selected, it should be noted that either criterion is somewhat arbitrary because the real test of the acceptability of a joint containing a given maximum amplitude level of indication is the performance of the joint under simulated service conditions.

The microstructural examination of the correlation study joints revealed the eccentric relative positions of the tongue and groove in some tubular assemblies. As indicated in subsequent paragraphs, the quality of certain brazed assemblies was considerably better than others, primarily in the area of the inner braze, even though all were prepared under essentially identical conditions. This behavior was believed to be directly related to the eccentricity problem, because the braze composition and corresponding solidification nature in the resultant wide and narrow spaced regions were found to be quite different. The best solution to the problem lies in redesigning of the components to effect uniform clearances at the brazing temperatures and below. An axially tapered tongue-in-groove design configuration for tubular assemblies is one promising approach. This design would result in uniform intercomponent spacings at the brazing temperature, providing that measures were taken to maintain the concentricity of the components during the brazing cycle. The necessary relative positions of the tongue and groove, before brazing, would have to be determined in order to compensate for the differential thermal expansion characteristics of tantalum and stainless steel. The tapered configuration, further, would require that the joint components be free to move in the axial direction during heating to the brazing temperature. By controlling the axial motion, as well as the diameters of the tongue and groove, the braze fill spacing all around could be adjusted to any desired value. Once the brazing alloy solidified during cooling, further relative component motion would be prohibited. If such a tapered joint design were utilized in fabrication of future joints, suitable postbraze inspection methods (ultrasonics) would have to be developed to verify their quality. In addition, testing of representative joints would have to be conducted under simulated service conditions to establish the validity of the new design for fabricating reliable assemblies.

FABRICATION OF PRODUCTION JOINTS

The requirements of this portion of the program were to fabricate twelve brazed tantalum/Type 316 stainless steel, tongue-in-groove, tubular transition joints using optimized techniques, and thereafter nondestructively inspect those assemblies by developed ultrasonic methods. The brazed assemblies will be tested elsewhere under a NASA contract to establish their suitability for use in the SNAP-8 Power Conversion System.

The tongue-in-groove design configuration for these production tubular assemblies is shown in Figure 2. The general method, employed in the preparation of the assemblies for brazing, was previously described (refer to the Materials and Processes Section). The brazing conditions used in fabrication of all tubular assemblies are summarized in Table IV.

It is believed that a brief review of the initial stages of this brazing program would be helpful at this point. The preliminary cooling rate study, using sheet material, indicated that optimum braze characteristics in tantalum/Type 316 stainless steel assemblies were achieved by cooling at a rate of 25°F (14°C)/minute from a brazing temperature of 2160°F (1182°C) to 1400°F (760°C), during which time the J-8400 braze alloy solidified. Therefore, tubular joints S/N 1 through S/N 10, as well as S/N 15, were brazed using these brazing parameters and the same shielding conditions. These included ultrasonic standard joints (S/N 1 to S/N 4, inclusive), correlation joints (S/N 5 to S/N 7, inclusive), and production joints (S/N 8, 9, 10, and 15). Rebrazing was attempted twice on joint S/N 1 before it was learned that its poor quality was caused by improper machining of components. Joints S/N 10 and S/N 15 were each successfully rebrazed once to improve their quality.

Joints S/N 12 and S/N 14 were used for directional solidification studies. This approach was eventually abandoned.

The ultrasonic inspection of the first eleven assemblies indicated a tendency in some cases for the formation of more microshrinkage porosity in the inner braze annular cavity than in the outer. This implied that the solidification has occurred from the outside to the inside of the assemblies. To reduce this tendency and minimize the amount of microshrinkage within the inner braze, the heat shielding used in preparation of the original joints was modified for the brazing of subsequent assemblies. The latter assemblies (S/N 11, 13, 16, 17, 18, 19, 20, 21, and 22) were prepared, and subsequently cooled at 25°F (14°C)/minute from the brazing temperature (shown in Table IV) to 1400°F (760°C). Temperature measurements made during the brazing operations for these production joints indicated small OD - ID transient and steady state temperature gradients (~ 20°F (11°C)), with the ID position being cooler. This was the desired condition which should have caused braze alloy freezing to occur in the desired direction; i.e., inside to outside. However, none of the assemblies were judged totally acceptable at that

TABLE IV

CONDITIONS USED IN THE VACUUM BRAZING OF TA/TYPE 316 SS TUBULAR BRAZED JOINTS

Joint No.(1)	Usage	Braze Temperature °F(2,3)	Time at Temp. (min)	Cooling Rate From Braze Temp. to 1400°F(4) (°F/min.)	Thermal Insulation Used During Brazing: Furnace	Thermal Insulation Used During Brazing: Joint	Remarks
1	Ultrasonic Standard	2160	5	25	Ten split tantalum discs separated by tantalum wires at top of furnace hot zone	None	Ultrasonically inspected Braze quality poor due to improper machining of components
		2200 (1st Rebraze)	2	25			
		2225 (2nd Rebraze)	1	23			
		2250 (3rd Rebraze)	1	24			
2	Ultrasonic standard - intentionally mis-brazed joint	2160	5	25	Same as Joint #1	Same as Joint #1	Ultrasonically inspected and sectioned for metallography
3	Ultrasonic Standard	2160	5	22	Same as Joint #1	Same as Joint #1	Assembly failed in brazed area during small hole machining
4	Ultrasonic Standard	2160	5	25	Same as Joint #1	Same as Joint #1	Assembly machined to produce small holes in braze area - used as ultrasonic calibration standard
5	Correlation Study Joint	2160	5	20	Same as Joint #1	Same as Joint #1	Metallographic examination of transverse planes compared with ultrasonic inspection data

(cont'd)

TABLE IV (cont'd)

Joint No.(1)	Usage	Braze Temperature °F(2,3)	Time at Temp. (min.)	Cooling Rate From Braze Temp. to 1400°F(4) (°F/min.)	Thermal Insulation Used During Brazing: Furnace	Thermal Insulation Used During Brazing: Joint	Remarks
6	Correlation Study Joint	2160	5	25	Same as Joint #1	Same as Joint #1	Assembly cracked during metallographic processing
7	Correlation Study Joint	2160	5	25	Same as Joint #1	Same as Joint #1	Assembly cracked during metallographic processing
8	Production Joint	2160	5	25	Same as Joint #1	Same as Joint #1	
9	Production Joint	2160	5	25	Same as Joint #1	Same as Joint #1	
10	Production Joint	2160 2200 (Rebraze)	5 2	25 25	Same as Joint #1	Same as Joint #1	
12	Directional Solidification Joint/Correlation Study Joint	2160 2190 (Rebraze)	5 2	150 150	Same as Joint #1	Tantalum component of joint shielded to reduce its cooling rate relative to the stainless steel component - Cylindrical tantalum shields used	Metallographic examination of transverse planes compared with ultrasonic inspection data
14	Directional Solidification Joint/Correlation Study Joint	2160 2190 (Rebraze)	5 2	25 25	Same as Joint #1	Same as Joint #1	Metallographic examination of longitudinal planes compared with ultrasonic inspection data

(cont'd)

TABLE IV (cont'd)

Joint No.(1)	Usage	Braze Temperature °F(2,3)	Time at Temp. (min.)	Cooling Rate From Braze Temp. to 1400°F(4) (°F/min.)	Thermal Insulation Used During Brazing: Furnace	Thermal Insulation Used During Brazing: Joint	Remarks
15	Production Joint	2160	5	25	Same as Joint #1	Same as Joint #1	
		2190 (Rebraze)	2	25			
16	Production Joint	2212	2	22	Same as Joint #1	Two cylindrical tantalum shields positioned between joint and furnace elements	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
19	Production Joint	2202	2	19	Same as Joint #1	Same as Joint #16 + four tantalum discs positioned atop tantalum component	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
11	Production Joint	2160	5	22	Same as Joint #1	Same as Joint #19	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
13	Production Joint	2170	5	21	Same as Joint #1	Same as Joint #19	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
17	Production Joint	2170	5	24	Same as Joint #1	Same as Joint #19	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
20	Production Joint	2160	5	25	Four tantalum discs separated by tantalum wires (shields not split) at top of furnace hot zone	Same as Joint #19	

(cont'd)

TABLE IV (cont'd)

Joint No.(1)	Usage	Braze Temperature °F(2,3)	Time at Temp. (min.)	Cooling Rate From Braze Temp. to 1400°F(4) (°F/min.)	Thermal Insulation Used During Brazing: Furnace	Thermal Insulation Used During Brazing: Joint	Remarks
20 (cont'd)		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
21	Production Joint	2170	5	26	Same as Joint #20	Same as Joint #19	
		2250 (Rebraze)	1	25	See Note (5)	See Note (5)	
18	Production Joint	2170	5	23	Same as Joint #20	Same as Joint #20	
		2210 (1st Rebraze)	2	24	See Note (5)	See Note (5)	
		2250 (2nd Rebraze)	1	25	See Note (5)	See Note (5)	
22	Production Joint	2170	5	23	Same as Joint #20	Same as Joint #19	
		2210 (1st Rebraze)	2	25	See Note (5)	See Note (5)	
		2250 (2nd Rebraze)	1	25	Same as Joint #1	Same as Joint #1	

NOTES:

(1) Joints are listed in the order in which they were brazed.

(2) Pt-Pt+10% RH thermocouples used, joints were positioned in furnace such that stainless steel component rested on tungsten hearth plate, all brazing performed in vacuum.

(3) Thermocouple attached to stainless steel outside wall at point opposite to base of tongue and groove.

(4) Cooling rates indicated were determined from stainless steel outside wall temperature measurements.

(5) Shielding used during rebraze cycles.
(a) Furnace - same as Joint #20
Joint - same as Joint #19

time based on the results of ultrasonic inspection. The difficulties may have been caused by the possible eccentric relationship of the tongue and groove diameters in those assemblies at the brazing temperature. Improving their quality to acceptable standards necessitated rebrazing. Therefore, two joints (S/N 18 and S/N 22) from the above group were rebrazed at 2210°F (1210°C) for two minutes in an attempt to improve their quality. Subsequent ultrasonic inspection of these joints indicated that an improved condition had been attained, although their quality was still not completely satisfactory, which implied that rebrazing at an even higher temperature was required. Thereafter, those two joints were rebrazed at 2250°F (1232°C) for one minute, reinspected, and found acceptable. Rebrazing at that temperature was believed to be successful primarily because of a reduction in the relative eccentricity of the tongue and groove. This reduction was attributed to differences in the thermal expansion rates of tantalum tongue and stainless steel groove which caused the latter to move closer to the tongue at the inner braze. Since the previous brazing cycles at 2160°F (1182°C) allowed the tantalum and stainless steel to reach the nearest point of approach at a single circumferential position, the relative motion produced by the 2250°F (1232°C) temperature cycles took place in the remaining portions of the joint, thereby reducing overall clearance at the inner braze annuli. Thereafter, all of the remaining questionable assemblies were rebrazed at 2250°F (1232°C) for one minute and slow cooled at 25°F (14°C)/minute to 1400°F (760°C). All of these assemblies were ultrasonically inspected, using the established methods, and found to be satisfactory. The ultrasonic examination of the tube joints was conducted first by "C-scan" techniques to determine the general quality of the brazes. If the general quality was good, "modified A-scan" (X-Y) recordings were obtained for more exacting determinations of quality. Figure 31 shows several of the X-Y recordings obtained from the ultrasonic inspection of production joint S/N 22.

After ultrasonic inspection, the production braze joints were machined to remove excess braze material from the outside tantalum surfaces, immediately above the tongue-in-groove areas, where the braze alloy had been preplaced. Figure 32 depicts two production assemblies; one after brazing and one after machining. All assemblies were then inspected to assure overall quality by visual examination, helium leak testing

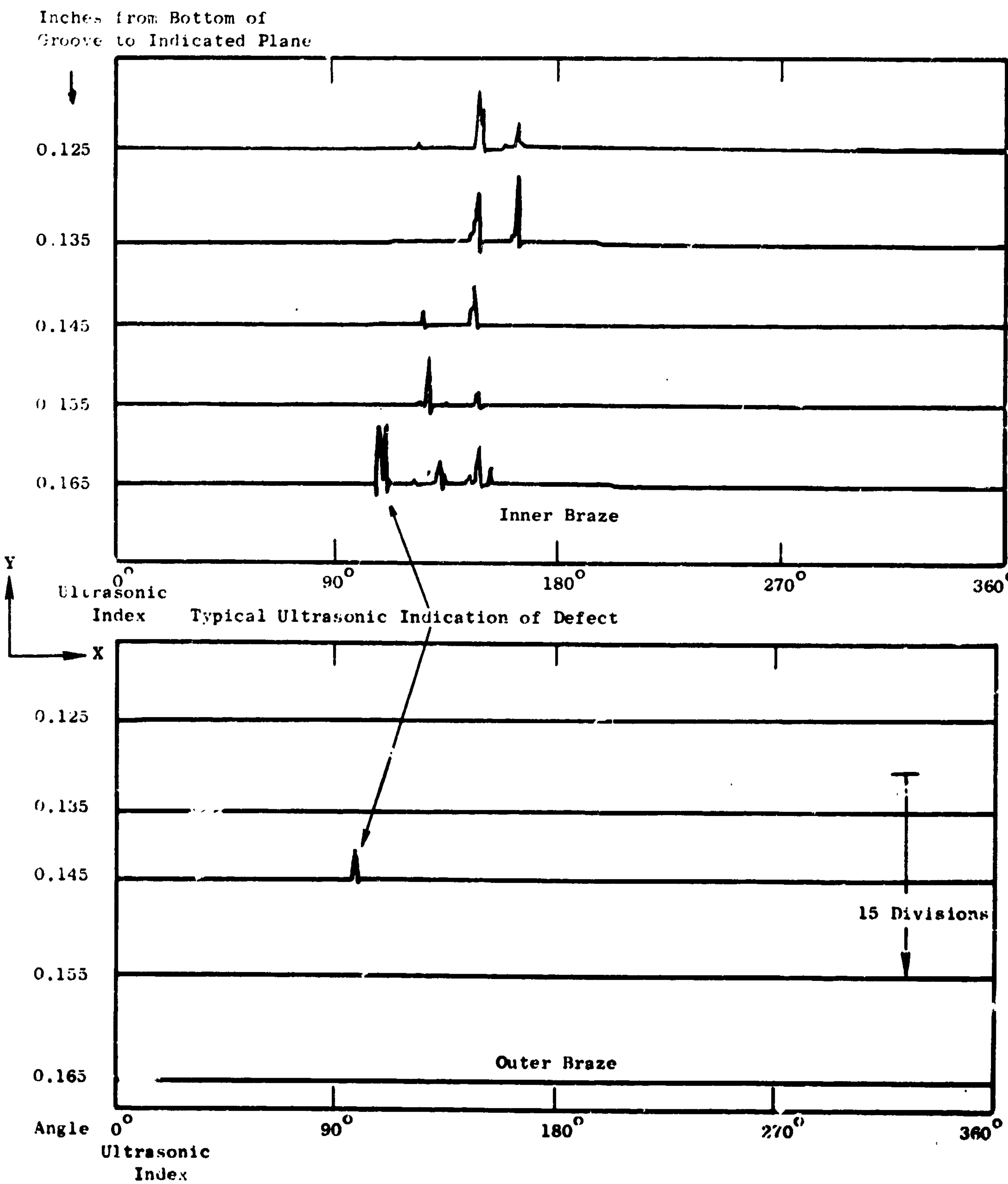


Figure 31. Ultrasonic "Modified A Scan" Presentations Obtained from Inspection of Tubular Ta/Type 316SS Production Brazed Joint S/N 22.

Figure 32. Ta/Type 316 SS Tubular Brazed Joints Before and After Machining to Remove Excess Braze Fillet Material. (P69-8-17L)

and dye penetrant ("Zyglo") inspection. The production joints were cleaned and packaged for shipment after those nondestructive tests had been completed.

IV. CONCLUSIONS

The experimentation to develop optimum methods for the brazing and ultrasonic inspection of tubular, tantalum/Type 316 stainless steel, tongue-in-groove design, transition joints produced several significant conclusions:

1. The methods, developed for the brazing of tantalum-to Type 316 stainless steel in this program, were shown to be capable of producing tubular assemblies with minimal braze micro-shrinkage. A number of such joints, prepared by those developed techniques, will be subjected to appropriate evaluation testing under the direction of NASA-LRC. The results of that testing will provide a meaningful definition of accepable braze characteristics in future tubular assemblies.

2. The utilization of a slow cooling rate (25°F (14°C)/minute)) during braze solidification produced tantalum/Type 316 stainless steel tubular braze assemblies having superior characteristics, in comparison with those evident in more rapidly cooled joints. Thus, slower cooling rates produced lesser braze micro-shrinkage, while not substantially increasing potentially detrimental braze-base metal reaction zones in either the tantalum or stainless steel joint components.

3. The tongue-in-groove design configuration for tubular brazed joints requires modification to eliminate the nonuniform spacing in the annular braze cavities and thereby optimize brazement characteristics. The concept believed to be most appropriate for achieving uniform spacings would incorporate an axially tapered tongue-and-groove configuration. That geometry, coupled with intercomponent guides to maintain concentricity of the tantalum and stainless steel tubes, would result in assemblies

having uniform and equal spacings of any desired dimensions.

4. The ultrasonic inspection procedure and apparatus employed were shown to have greater sensitivity than that required to detect those defects believed to be detrimental to the strength of a brazed tantalum/Type 316 stainless steel tongue-in-groove joint. For future inspections of tubular transition joints of this type, decreased sensitivity levels should be utilized so that only the more severe defects would appear on the plan view presentation.

5. The developed ultrasonic inspection system has demonstrated the capability for resolving individual defects in the brazed areas. The system has sufficient power to permit inspection of the inner braze annuli (i.e., at the inside of the tongue and groove) at the same sensitivity levels used in scanning the outer braze annuli.

6. Brazing of tubular assemblies, under conditions believed to be conducive to directional braze solidification, did not enhance the brazing characteristics over those obtained by the use of a slow cooling rate during braze freezing.

7. Limited elevated temperature tensile testing of brazed tongue-in-groove sheet specimens indicated that the solidified J-8400 braze alloy could contain microshrinkage occupying up to 25 percent of the total braze volume and still withstand stresses at 2000°F (1093°C), which would induce failure of the stainless steel joint components. The braze alloy was also found to be resistant to crack propagation at that temperature under shear loading conditions. Determination of the effects of different braze microshrinkage levels on the shear load carrying capability of tantalum/Type 316 stainless steel assemblies would require modification of the specimen design configuration to cause failures to occur in the braze material instead of the base material.

8. The as-brazed hardness of the J-8400 braze alloy exceeds that of the tantalum and Type 316 stainless steel parent metals by a substantial margin, regardless of the brazing thermal cycle employed. Further braze chemistry changes produce no apparent effects on the overall braze hardness. The extent of braze constituent penetration into the stainless steel of tubular assemblies is greater at the outside of the tongue-in-groove than at the inside. The formation of an intermetallic phase at tantalum/braze interfaces, early in the brazing cycle, limited the amount of further braze reactions in the tantalum components.

V. REFERENCES

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